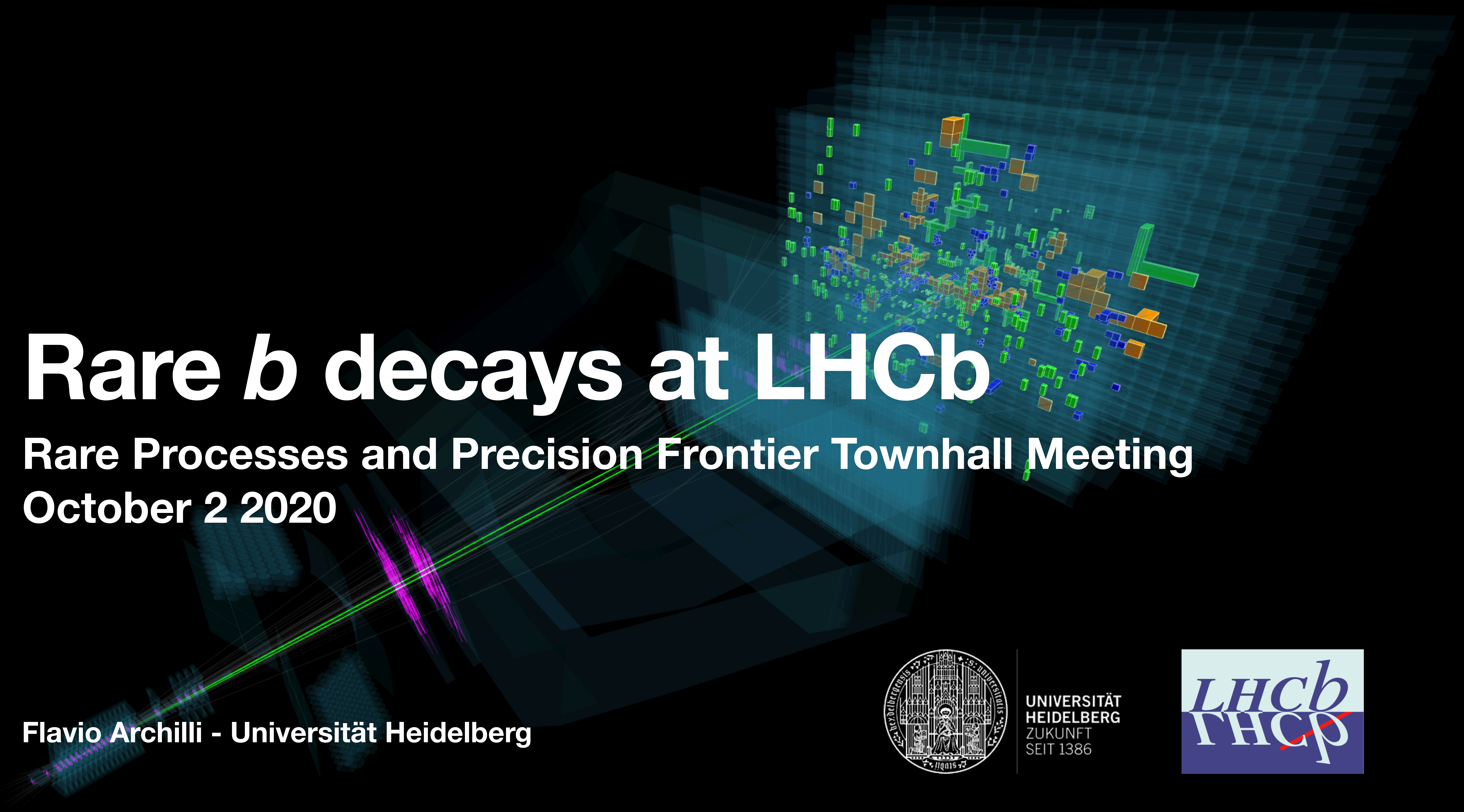


Rare *b* decays at LHCb

Rare Processes and Precision Frontier Townhall Meeting

October 2 2020

Flavio Archilli - Universität Heidelberg

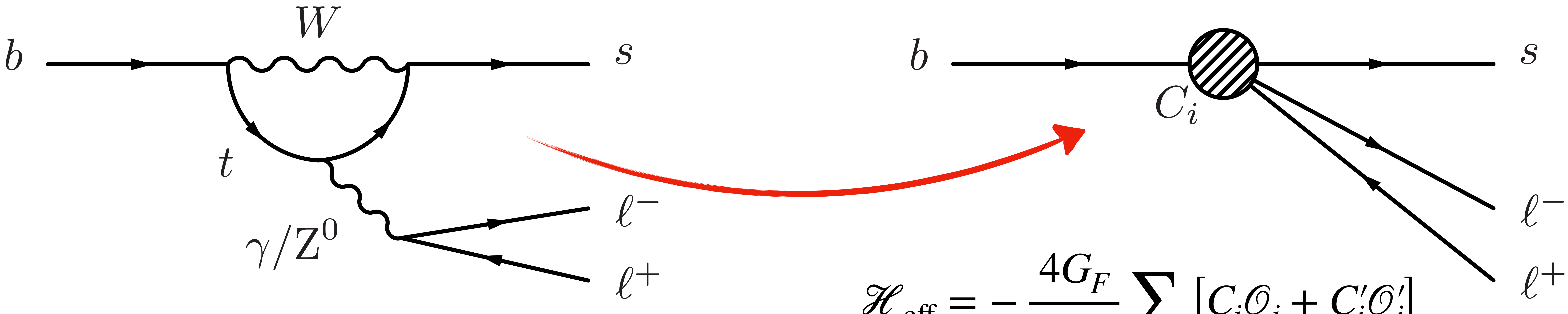
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

LHCb

a minimal introduction ...

- FCNC process can occur only via quantum-loop transitions strong suppression due to CKM hierarchy $\rightarrow \mathscr{B} \sim 10^{-6} - 10^{-10}$

- New Physics contribution can arise at the same level of or larger than SM



$$\mathscr{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}\pi}\sum\left[C_i\mathcal{O}_i + C_i'\mathcal{O}_i'\right]$$

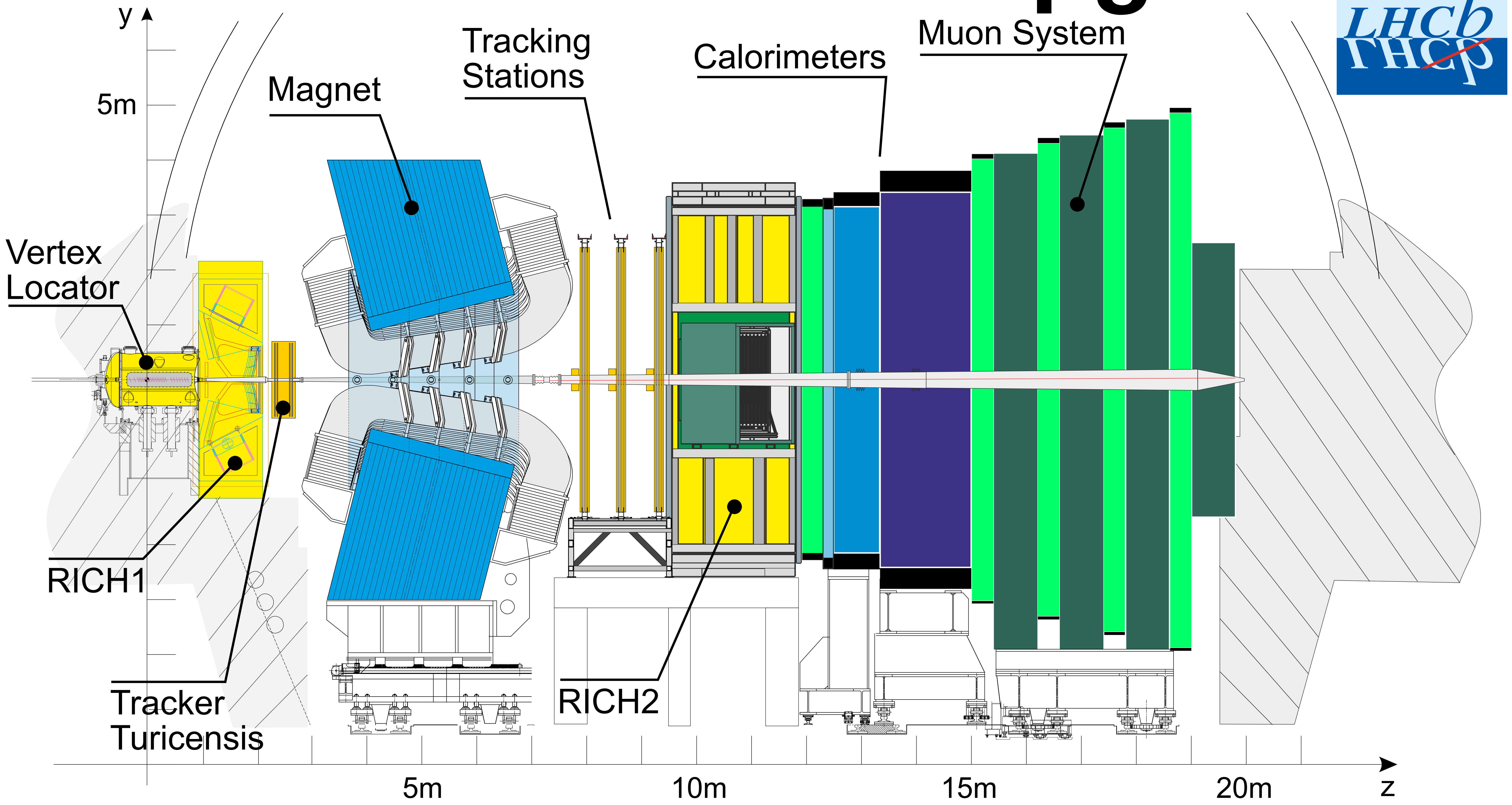
- Many results already presented on Monday (see slides here)

... and a glimpse of the detector and upgrades

- Large $pp \to b\bar{b}X$ cross section
- $b\bar{b}$ produced at low angle → forward spectrometer
- b-hadrons produced with large boost → excellent vertex resolution for background reduction

- Excellent muon identification (ε_μ = 98%) and low misID $\varepsilon_{h\to\mu} \sim 0.5\%$
- High trigger efficiency on B decays with muons (ε_μ~90%)
- Well suited for $b \to s\ell\ell$ analyses

Preparing the detector for a bright future!



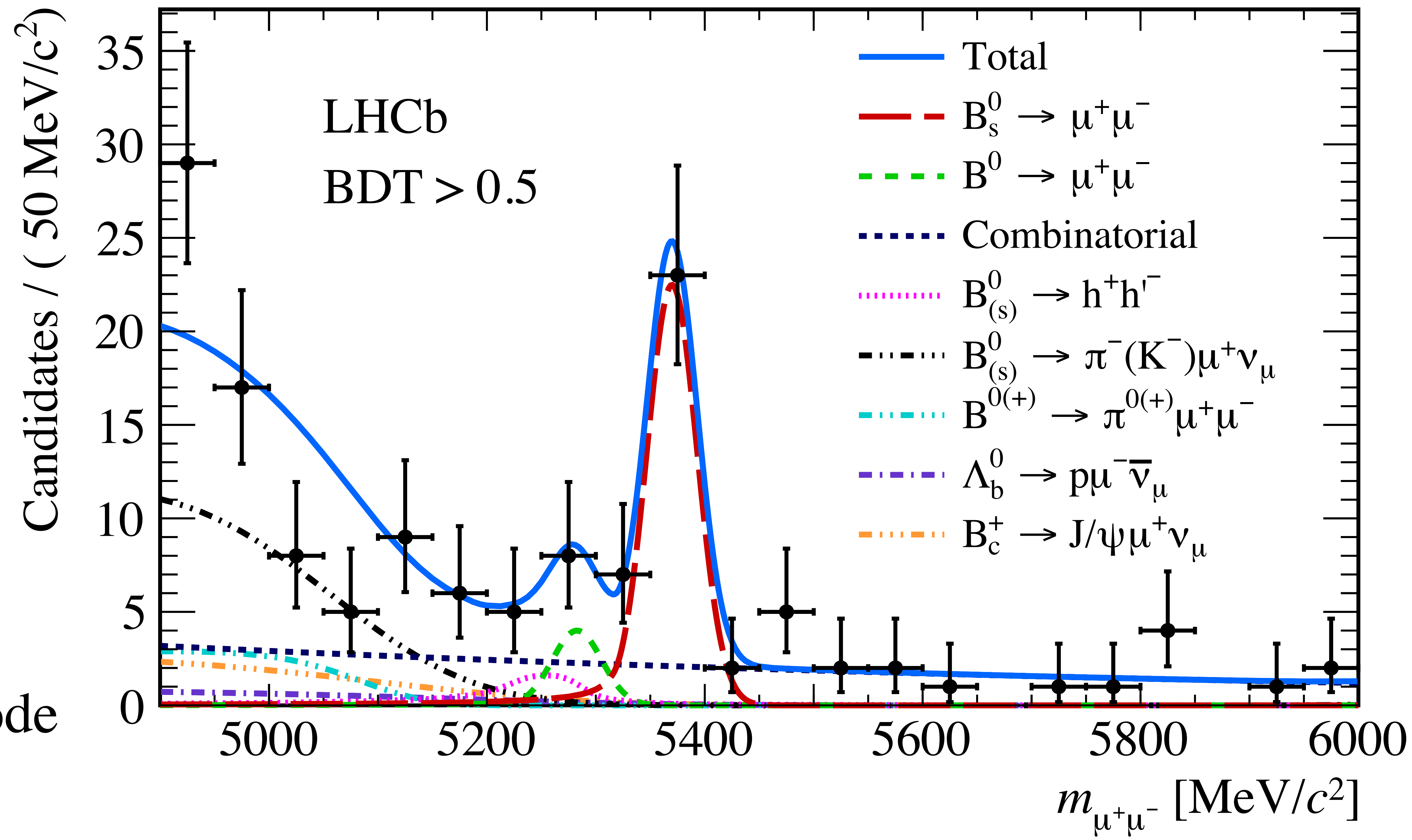
LHCb | LHCb Upgrade I | LHCb Upgrade II

Run1 - Run2		Run3		Run4		Run5		Run6
$\mathcal{L}_{int}$ = 10 fb^{-1}	LS2 Injector upgrades	$\mathcal{L}$ = 2 x 10^{33}	LS3 HL-LHC - ATLAS/CMS Phase 2 upgrades	$\mathcal{L}_{int}$~ 50 fb^{-1}	LS4	$\mathcal{L}$ = 1-2 x 10^{34}	LS5	$\mathcal{L}_{int}$~ 300 fb^{-1}
2010 2018	2019 2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030	2031	2032 2033 2034	2035	2036 2040

Purely leptonic rare decays

LHCb PRL 118, 191801 (2017)

- Theoretically clean, additionally suppressed by helicity
  - $\mathcal{B}_{\mathrm{SM}}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
  - $\mathcal{B}_{\mathrm{SM}}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
- LHCb results @ Run1+1.4fb^{-1}:
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 95 % CL
- Main systematics from f_s/f_d and BF of normalisation mode
- At 300fb^{-1} (with conservative assumption on sys ~4%):
  - $\Delta\mathcal{B}(B_s^0 \to \mu\mu) \sim 0.16 \times 10^{-9}$
  - $\sigma(\mathcal{B}(B^0 \to \mu\mu)/\mathcal{B}(B_s^0 \to \mu\mu)) \sim 10\,\%$

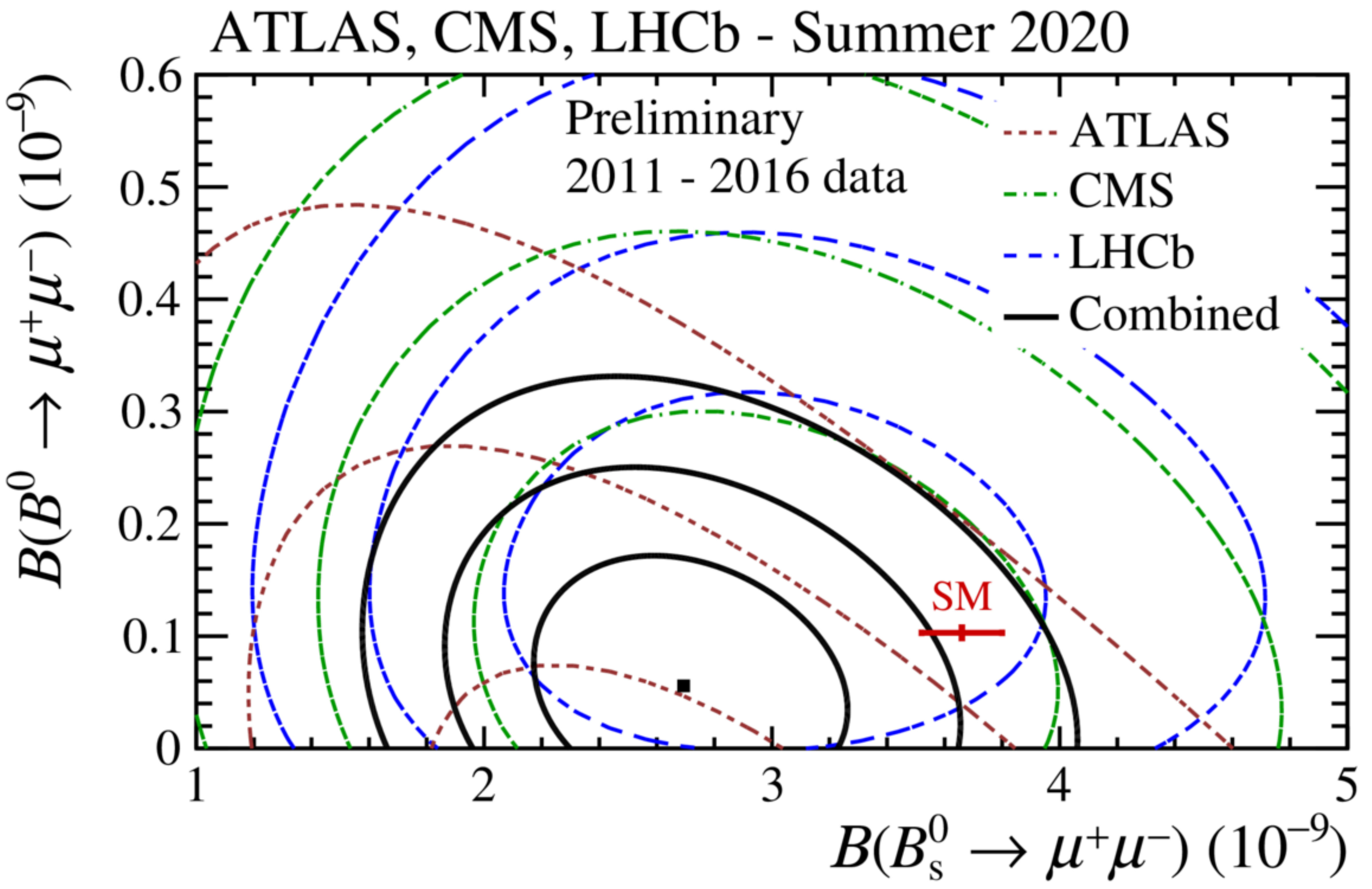


LHCB-CONF-2020-002
CMS PAS BPH-20-003
ATLAS-CONF-2020-049

LHC combination

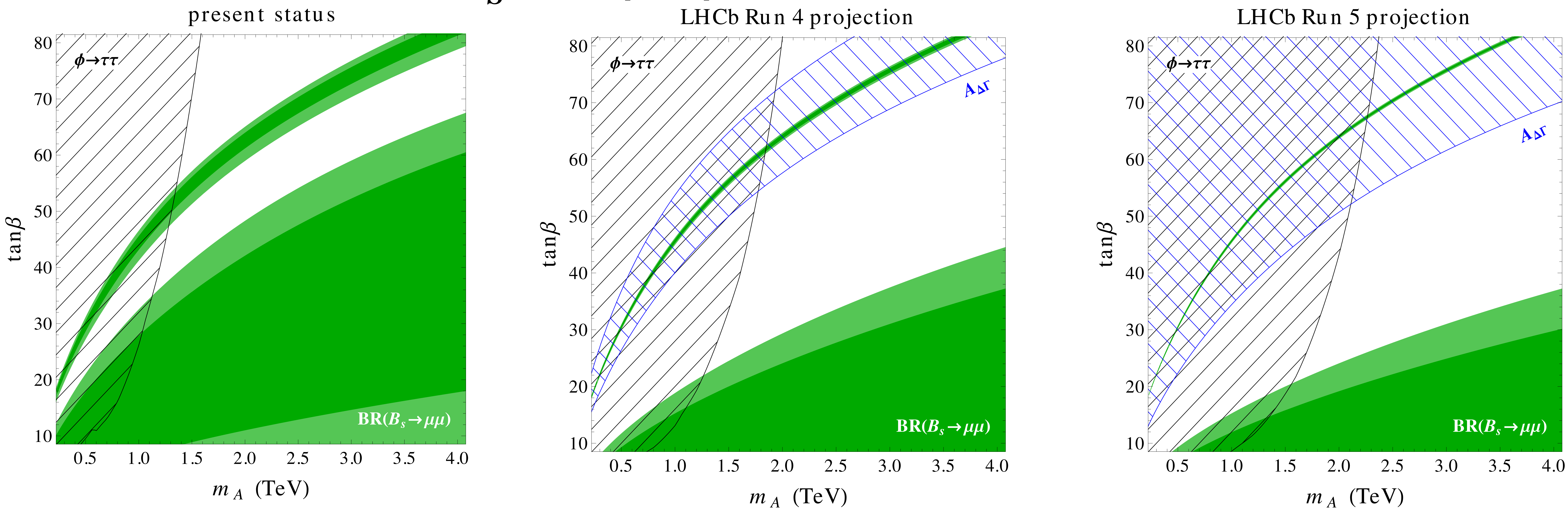
- Combination of the measurements from ATLAS, CMS, and LHCb based on Run-1 and 2016 data samples:
  - $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$
  - $\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ @ 95 % CL

- **Compatibility with the SM in 2D: 2.1σ**



Prospects for $B_s^0 \to \mu^+\mu^-$

Altmannshofer et al. JHEP05(2017)076



- In MSSM $\mathcal{B}(B_s^0 \to \mu\mu) \propto \tan^6\beta / m_A^4$
- With full Run1+Run2 $\sigma(\mathcal{B}(B_s^0 \to \mu\mu))/\mathcal{B}(B_s^0 \to \mu\mu) \sim 14\,\%$ can be reached → Together with ATLAS and CMS $\sigma(\mathcal{B}(B_s^0 \to \mu\mu))/\mathcal{B}(B_s^0 \to \mu\mu) \sim 7\,\%$, which is the expected uncertainty at the end of Run4 for LHCb only
- Complementary to direct searches of ττ resonances

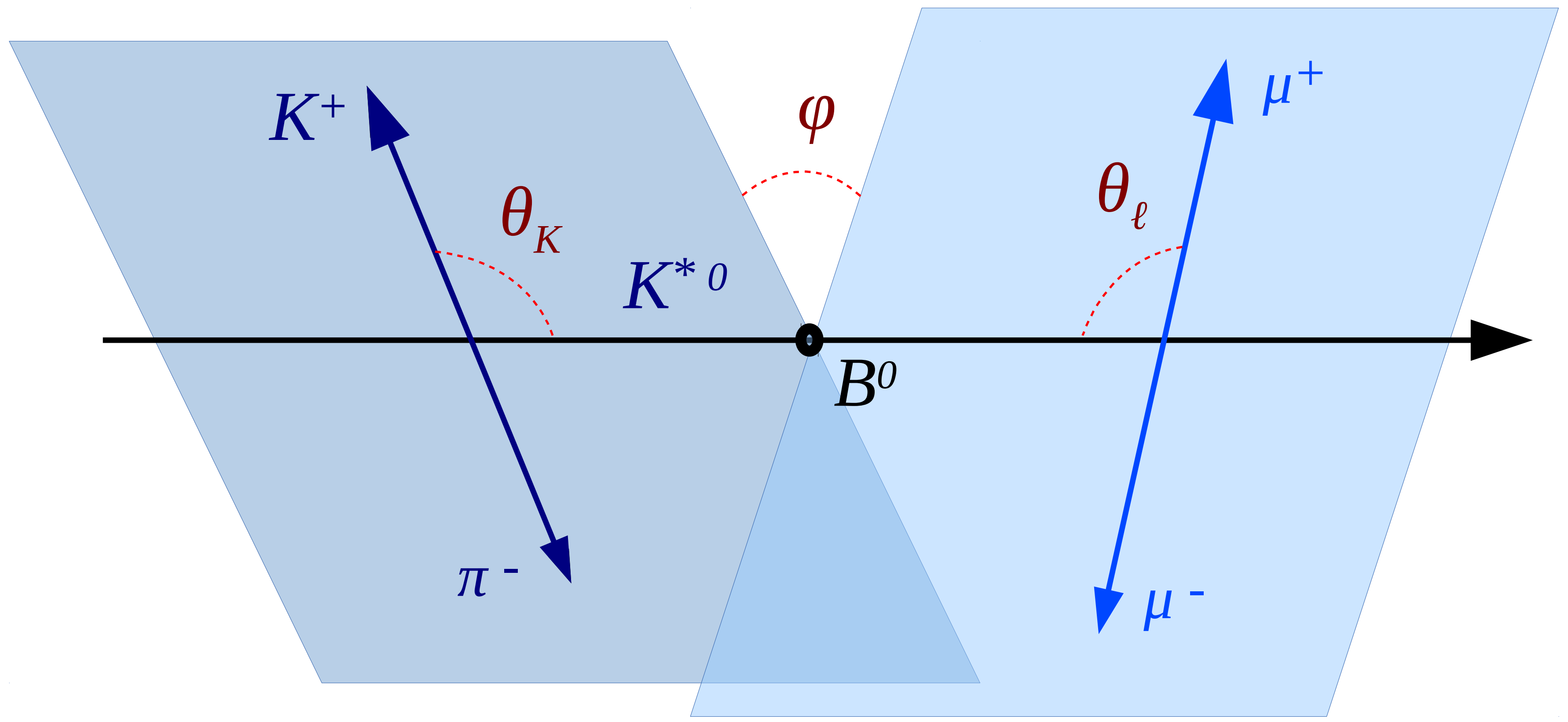
Electroweak penguins: an example

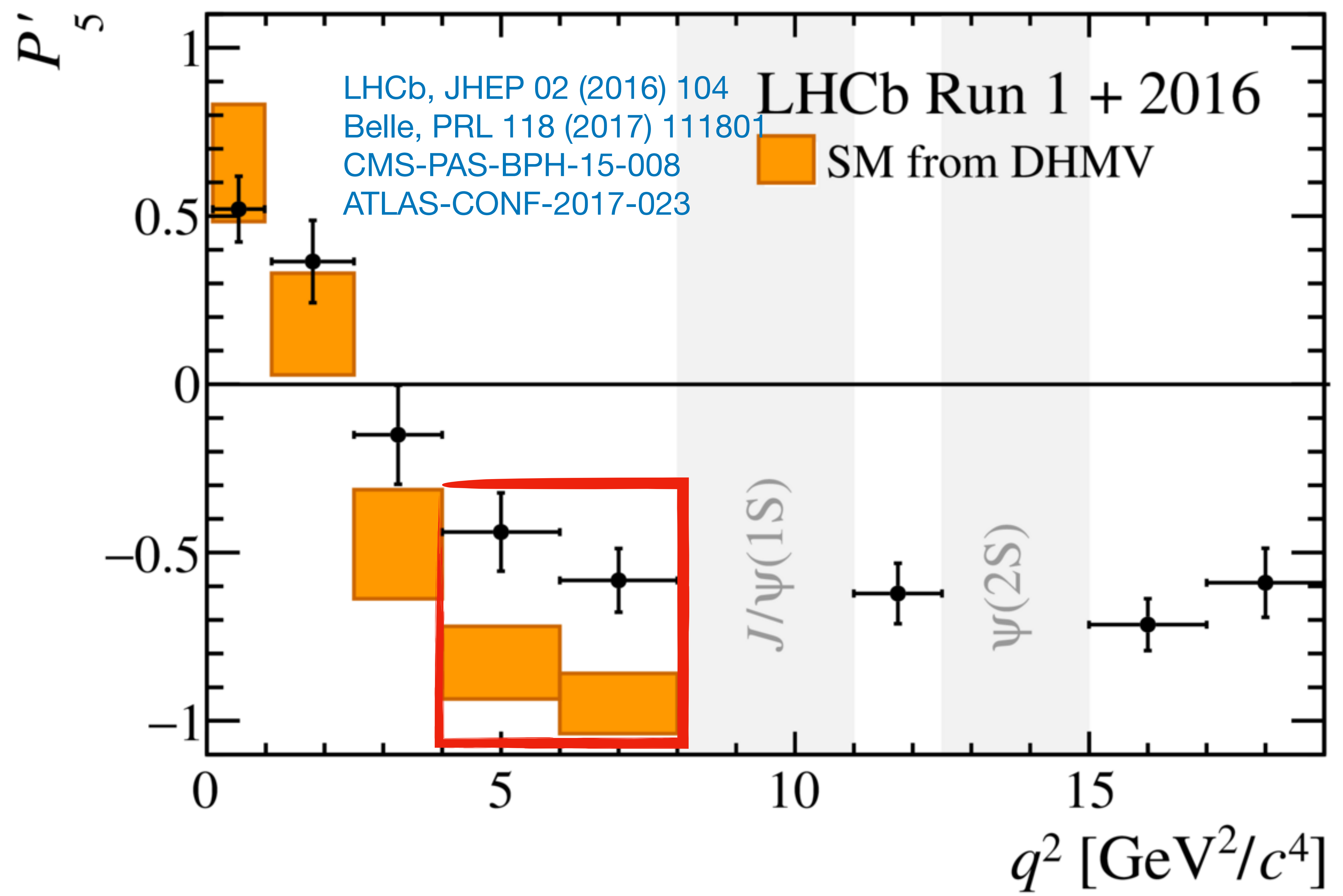
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- F_L, A_{FB}, S_i depend on C_7 C_9 and C_{10} and FF → large uncertainty at leading order

- Re-parametrisation of the angular coefficients with reduced dependency on FF

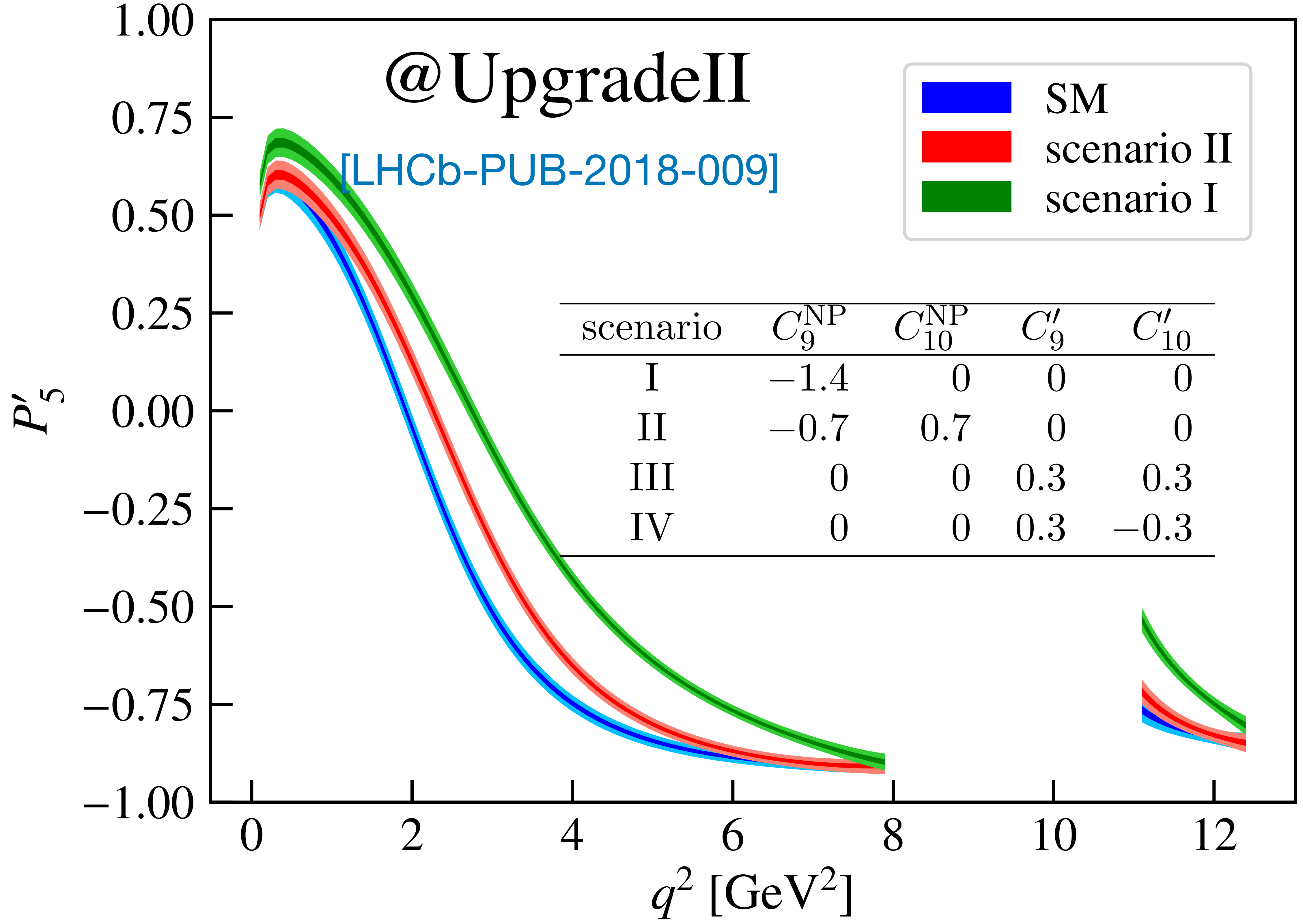
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

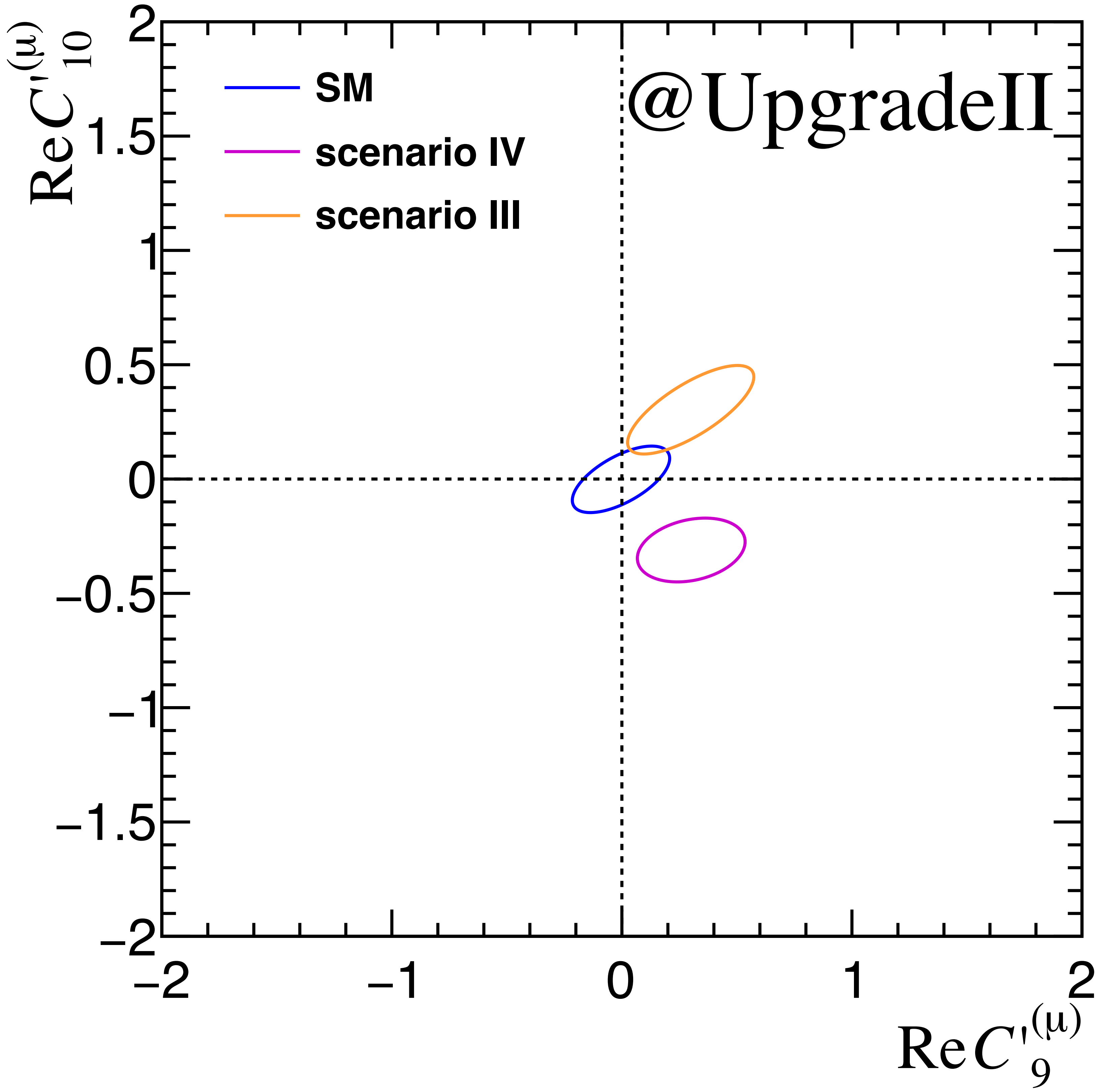




$B^0 \to K^{*0}\mu\mu$ angular analysis prospects

- For C_9, C_{10} form factor uncertainties cause saturation at $\sim 30\,\mathrm{fb}^{-1}$ → Will need theory to improve



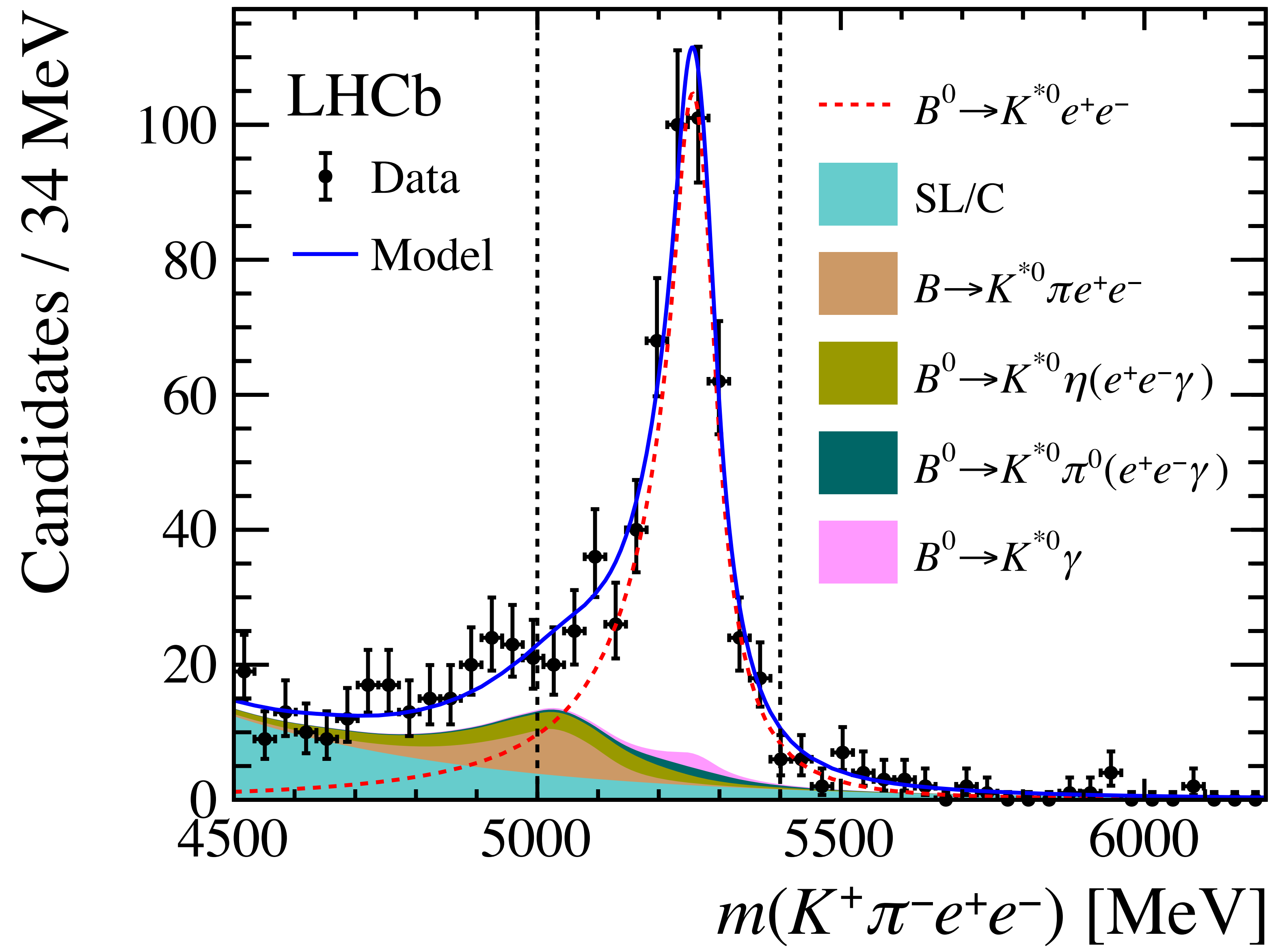


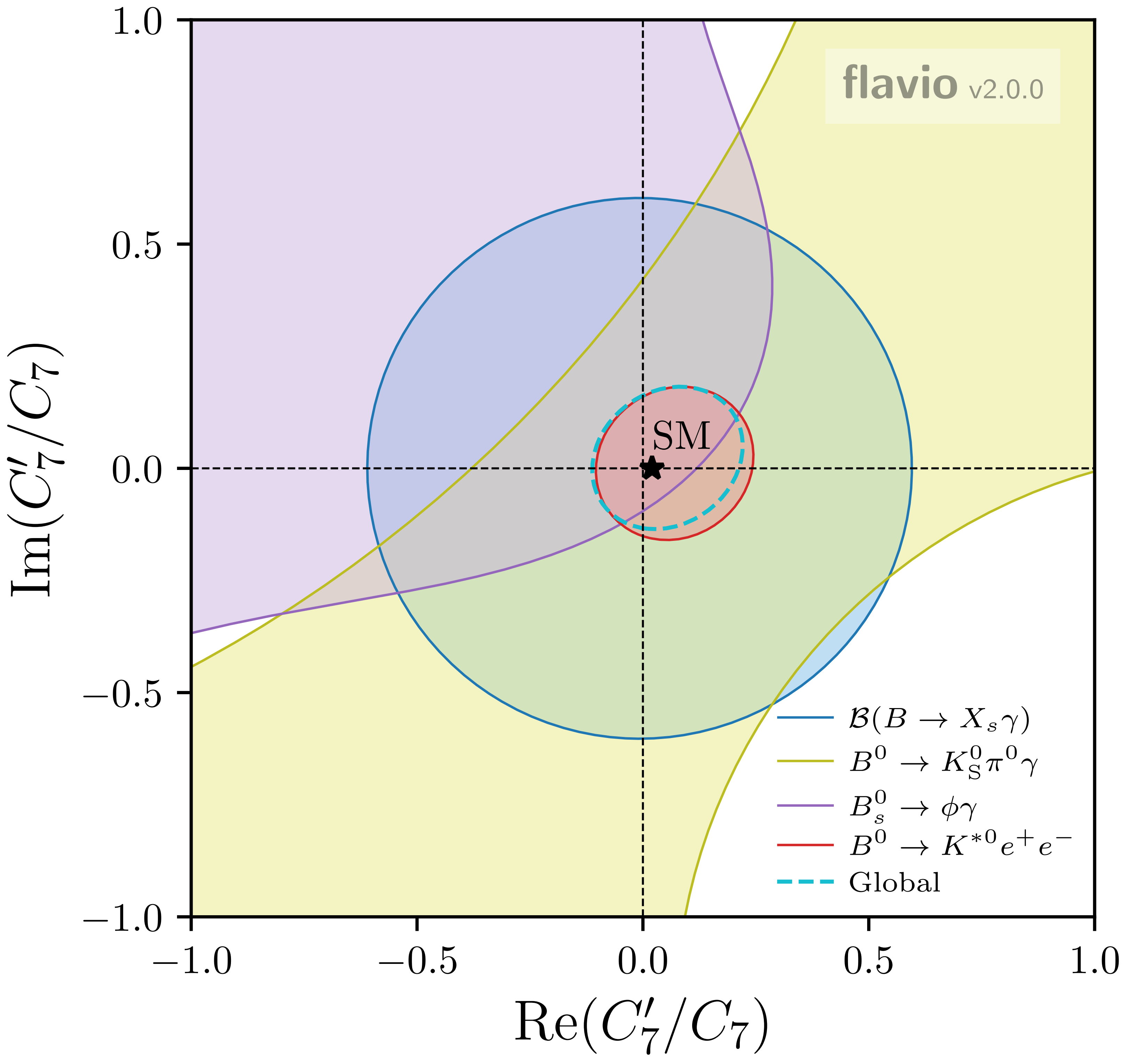
- Large data set @Upgrade II, (~440 000 fully reconstructed $B^0 \to K^{*0}\mu^+\mu^-$ decays), it will make possible a precise determination of the angular observables in narrow bins of q^2 or using a q^2-unbinned approach

LHCb-PAPER-2020-020

Probing C7

- $b \to s\gamma$ transition rates proportional to C_7
- photon polarisation mainly LH
- BF's, CP asymmetries and photon polarisation precision improves with 300fb^{-1}
- Access also to $b \to d\gamma$ with larger CP asymmetry expected
- Alternative way to measure photon polarisation is to use $b \to se^+e^-$ decays at very low q^2 ($B \to K^*e^+e^-$)





Summary

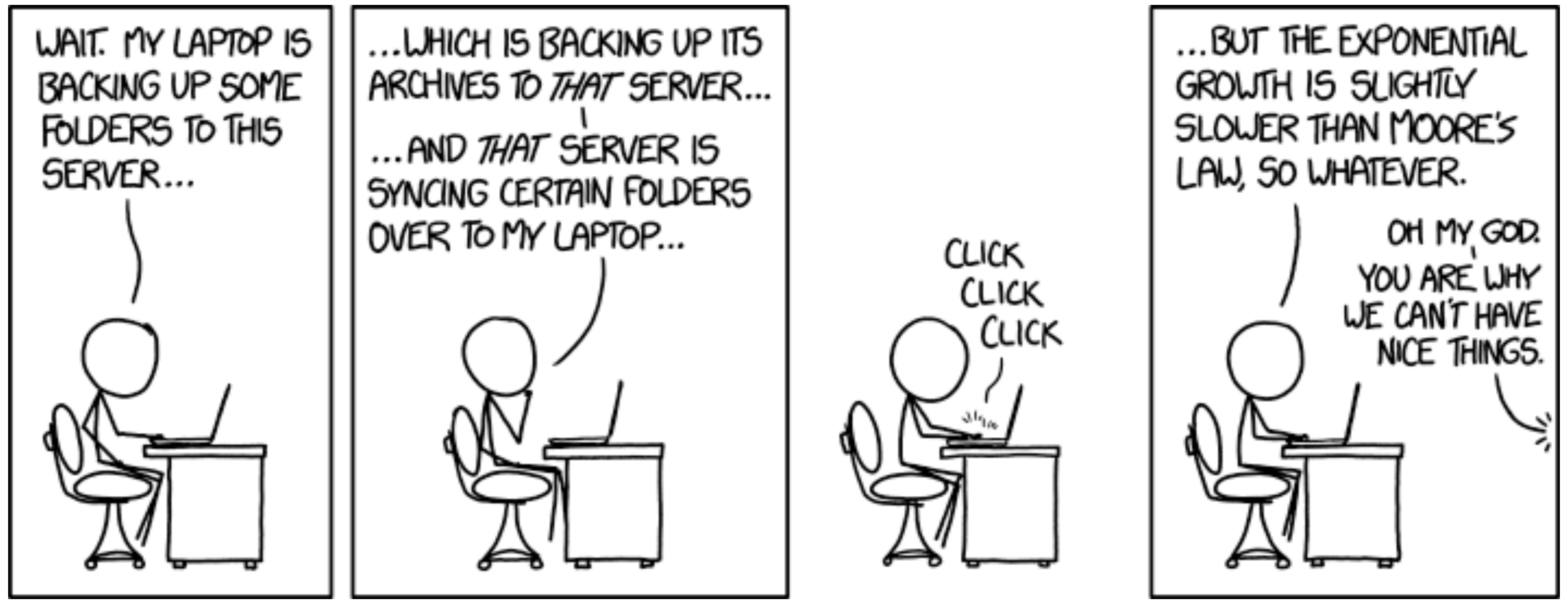
FCNC processes are powerful tools to probe for NP and current anomalies in $b \to s\ell\ell$ processes are suggesting possible effects.

Update of the current analysis can possibly show an evidence of NP already with full Run2 data.

(Not shown today) LFV searches can strongly constraints the parameters space of several BSM models.

Future upgrades will provide the statistical power to discriminate between NP models, and provide access to additional observables.

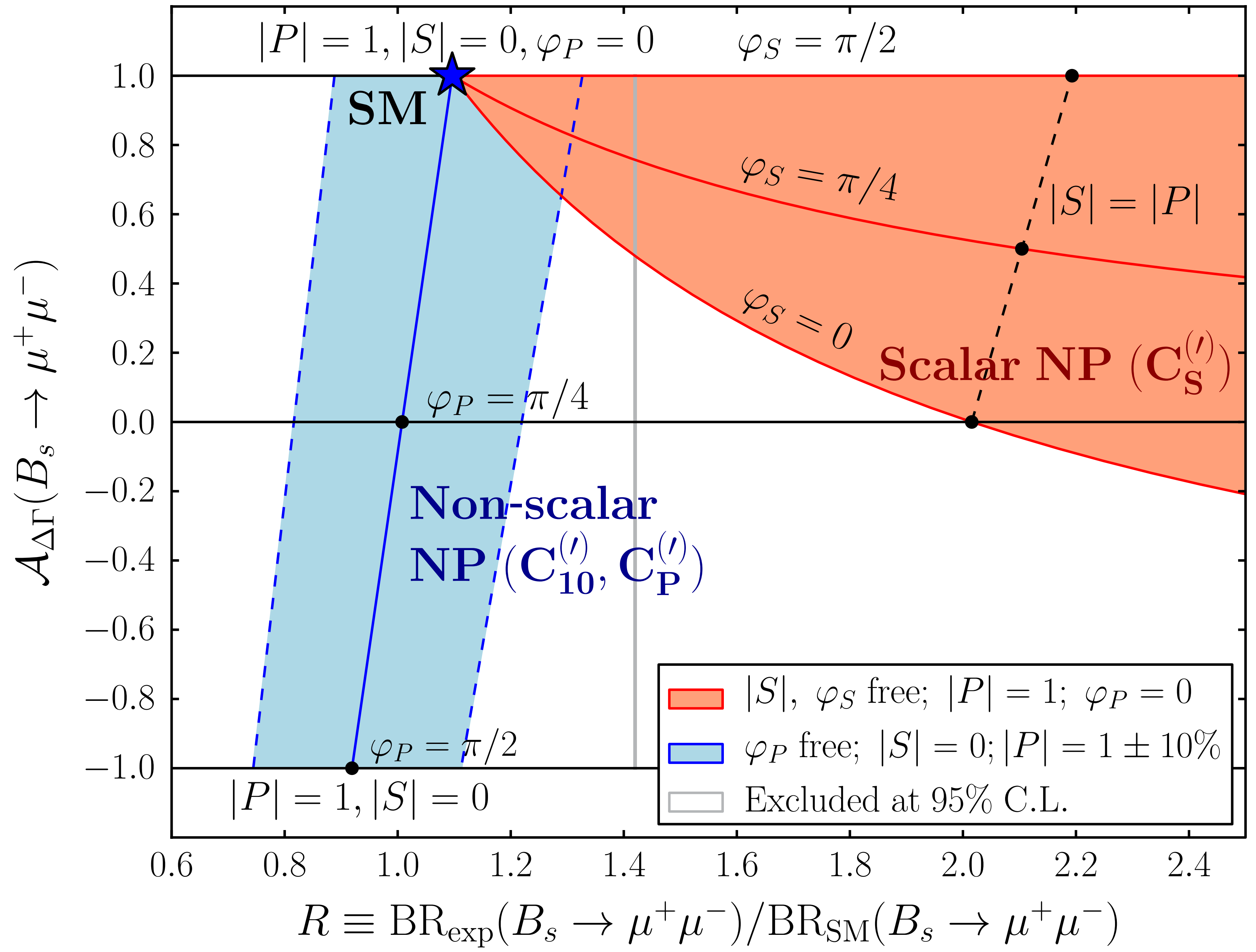
Backup


WAIT. MY LAPTOP IS BACKING UP SOME FOLDERS TO THIS SERVER...
...WHICH IS BACKING UP ITS ARCHIVES TO *THAT* SERVER...
...AND *THAT* SERVER IS SYNCING CERTAIN FOLDERS OVER TO MY LAPTOP...
CLICK
CLICK
CLICK
...BUT THE EXPONENTIAL GROWTH IS SLIGHTLY SLOWER THAN MOORE'S LAW, SO WHATEVER.
OH MY GOD.
YOU ARE WHY WE CAN'T HAVE NICE THINGS.

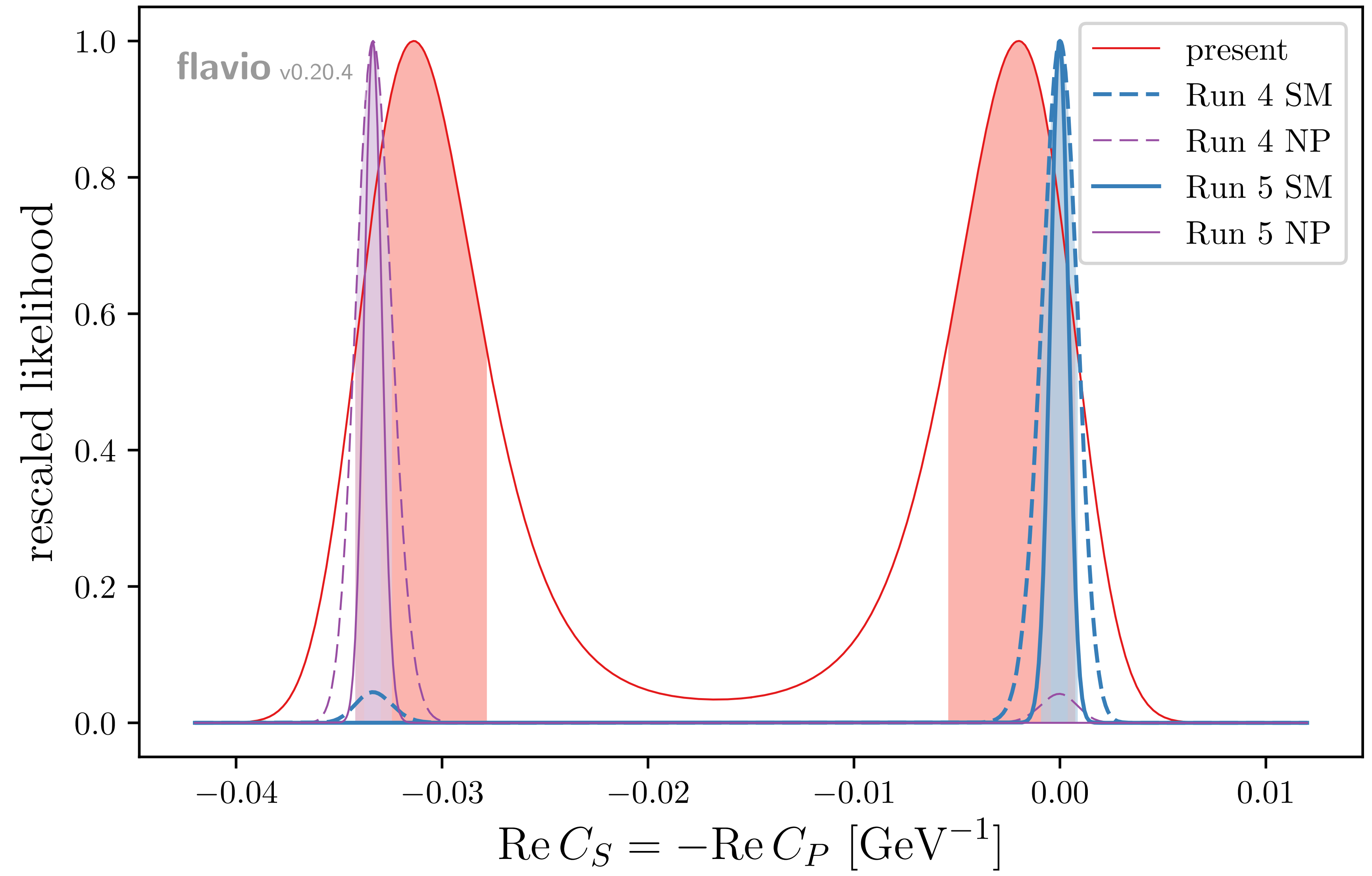
$B_s^0 \to \mu^+\mu^-$ effective lifetime

- With 300fb^{-1} precise measurement of additional observables: effective lifetime $\tau_{\mu\mu}^{\rm eff}$ and time-dependent CP-asymmetry $S_{\mu\mu}$
- Both sensitive to (pseudo-)scalar contribution, (CP)CS
    - Recent LHCb measurement: $\tau_{\mu\mu}^{\rm eff} = 2.04 \pm 0.44 \pm 0.05$ ps
    - Run5-6: $\sigma(\tau_{\mu\mu}^{\rm eff}) \sim 2\,\%$
- Assuming a tagging power ~3.7%, $S_{\mu\mu}$ @Run5-6:
    - $\sigma(S_{\mu\mu}) \sim 0.2$
- with a tagging power of ~8% and current analysis performance
    - $\sigma(S_{\mu\mu}) \sim 0.1$

JHEP 1307 (2013) 77

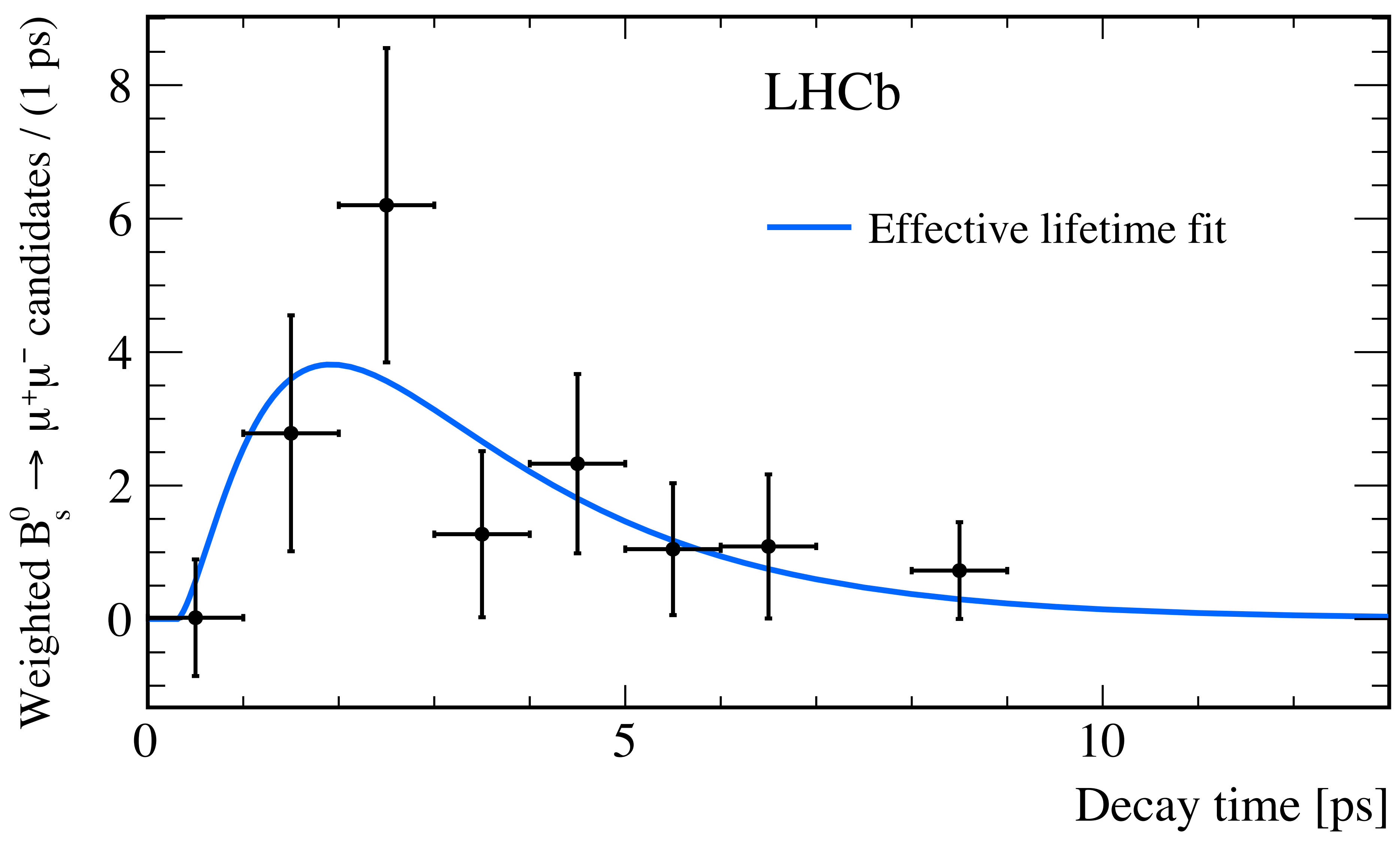


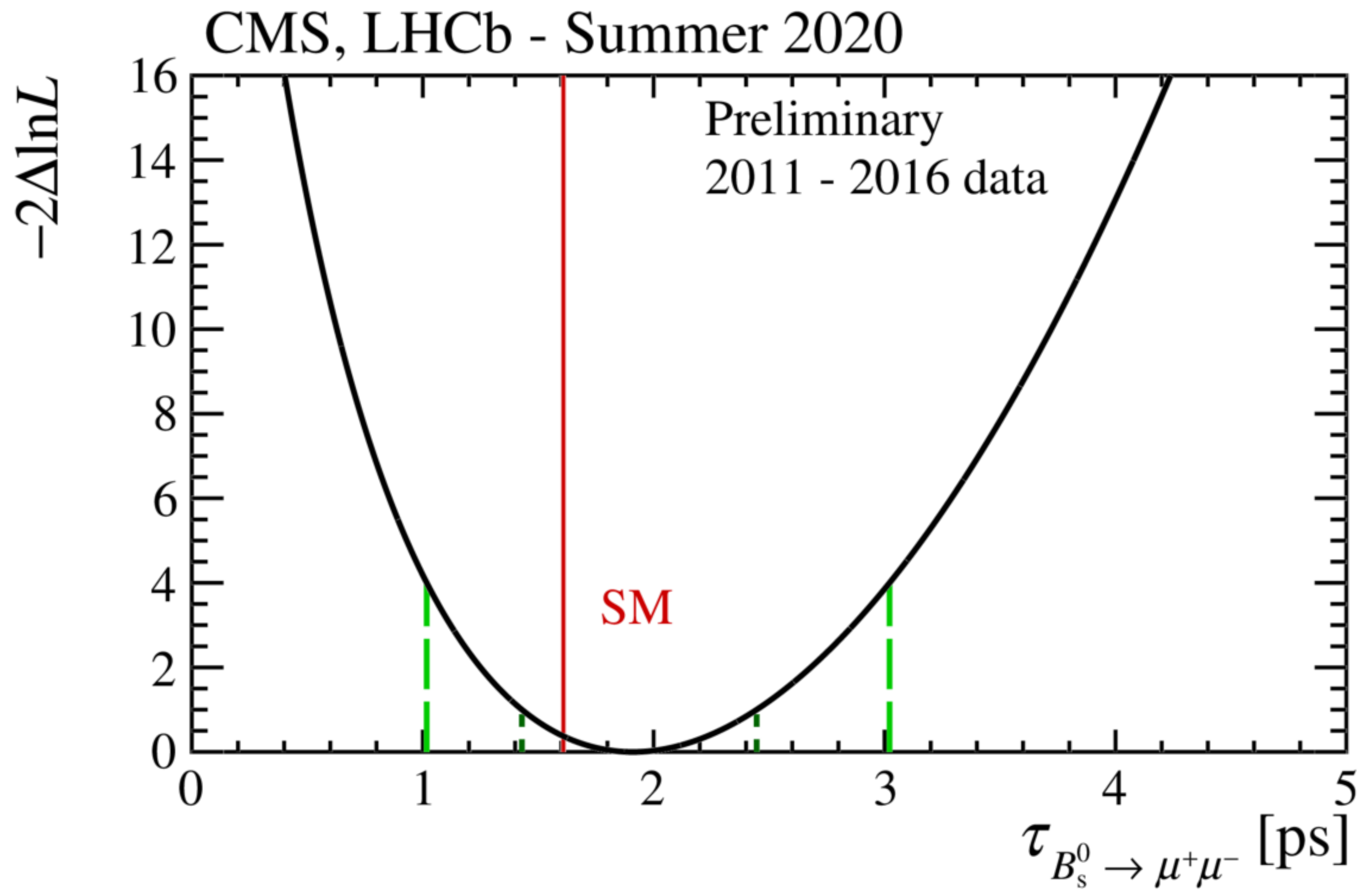
Straub JHEP 05 (2017) 076



$B_s^0 \to \mu^+\mu^-$ effective lifetime

- With 300fb^{-1} precise measurement of additional observables: effective lifetime $\tau_{\mu\mu}^{\text{eff}}$ and time-dependent CP-asymmetry $S_{\mu\mu}$
- Both sensitive to (pseudo-)scalar contribution, $(C_P)C_S$
  - Recent LHCb measurement: $\tau_{\mu\mu}^{\text{eff}} = 2.04 \pm 0.44 \pm 0.05\,\text{ps}$
  - Combined with CMS: $\tau_{\mu\mu} = 1.91^{+0.37}_{-0.35}$ ps
  - Run5-6: $\sigma(\tau_{\mu\mu}^{\text{eff}}) \sim 2\,\%$
- Assuming a tagging power ~3.7%, $S_{\mu\mu}$ @Run5-6:
  - $\sigma(S_{\mu\mu}) \sim 0.2$
- with a tagging power of ~8% and current analysis performance
  - $\sigma(S_{\mu\mu}) \sim 0.1$



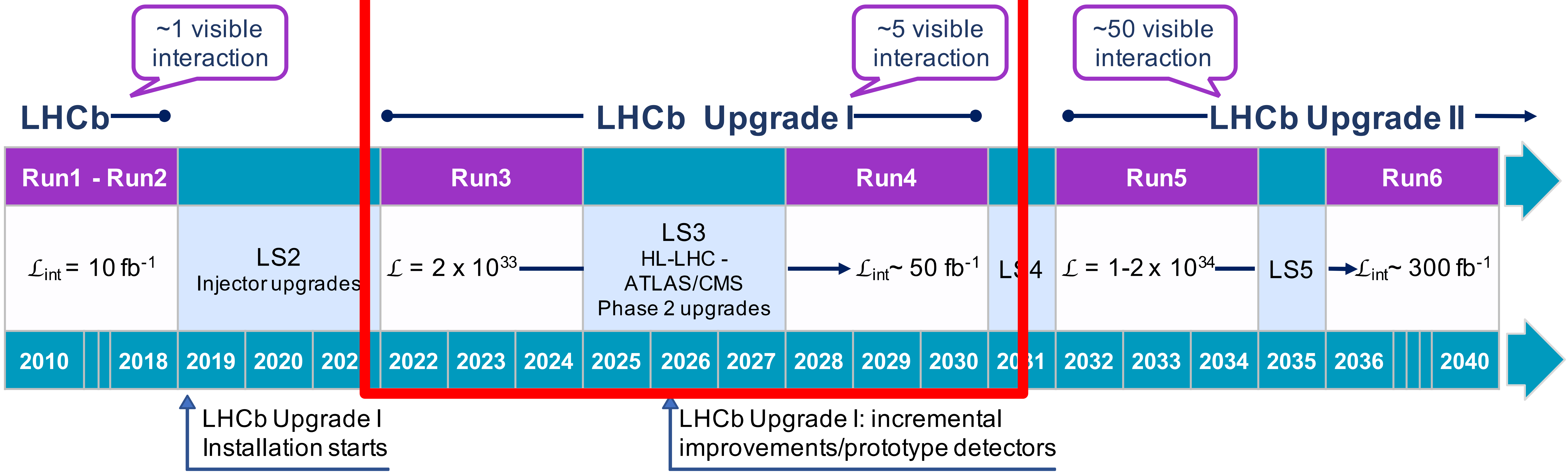


$B^0_{(s)} \to \mu^+\mu^-$ projections

		current	9fb^{-1}	23fb^{-1}	300fb^{-1}
LHCb	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$\pm 0.6^{+0.3}_{-0.2} \times 10^{-9}$		$\pm 0.30 \times 10^{-9}$	$\pm 0.16 \times 10^{-9}$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)}$	$90\,\%$		$34\,\%$	$10\,\%$
	$\tau_{\mu^+\mu^-}$ (ps)	$\pm 0.44 \pm 0.05$		± 0.16	± 0.04
			150fb^{-1}	**300fb^{-1}**	**3000fb^{-1}**
CMS	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	${}^{+0.7}_{-0.6} \pm 0.2 \times 10^{-9}$		$\pm(0.43 - 0.46) \times 10^{-9}$	$\pm(0.39) \times 10^{-9}$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)}$			$50\,\%$	$21\,\%$
	$\tau_{\mu^+\mu^-}$ (ps)	${}^{+0.61}_{-0.44}$		± 0.15	± 0.05
ATLAS	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	${}^{+0.8}_{-0.7} \times 10^{-9}$	$\pm 0.83 \times 10^{-9}$		$\pm(0.46 - 0.55) \times 10^{-9}$
	$\mathcal{B}(B^0 \to \mu^+\mu^-)$	$< 2.1 \times 10^{-10}$	$\pm 1.43 \times 10^{-10}$		$\pm(0.28 - 0.54) \times 10^{-10}$

[LHCB-PUB-2018-009] [ATL-PHYS-PUB-2018-005] [CMS PAS FTR-14-013/-015]

Upgrade and plans



- Preparing the upgrade for Run3 and Run4 during LS2
  - Full software trigger and new readout system, all detector at 40MHz (32 Tbps throughput)
  - Replace tracking detectors + PID + VELO, $\mathscr{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Consolidate PID, tracking and ECAL during LS3
- Phase-II upgrade during LS4:
  - New detector technologies, $\mathscr{L} = 1.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Detector upgrade I

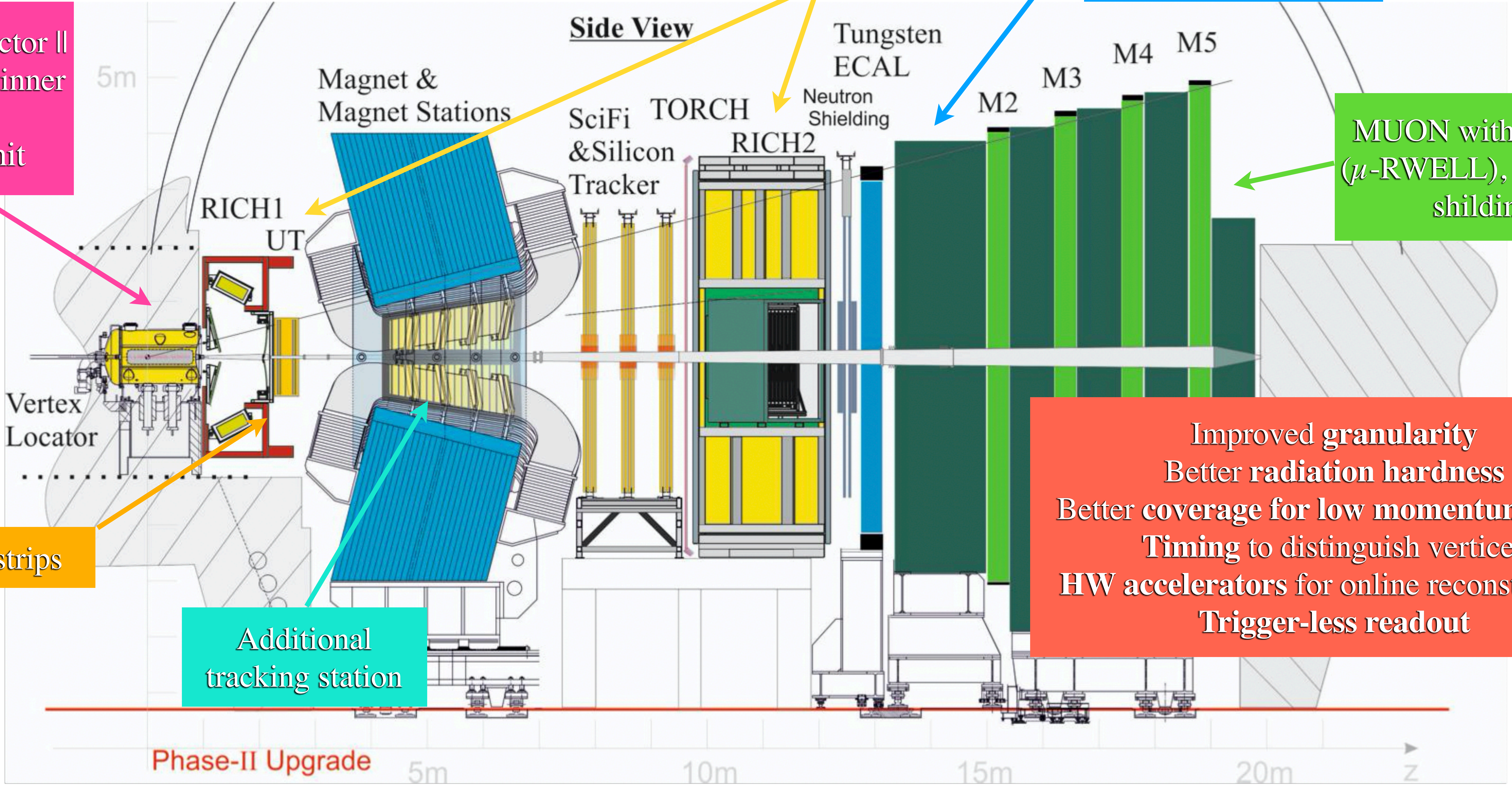
Detector upgrade II

RICH with new photon detectos
$\sigma_t < 100$ ps/photon,
TORCH detector

ECAL with finer segmentation and timing with
$\sigma_t \sim 20 - 50$ ps

New Vertex Detector ll smaller pixels, thinner sensors,
$\sigma_t < 200$ ps/hit

MUON with MPGD (μ-RWELL), modified shilding



Improved **granularity**
Better **radiation hardness**
Better **coverage for low momentum** tracks
Timing to distinguish vertices
HW accelerators for online reconstruction
Trigger-less readout

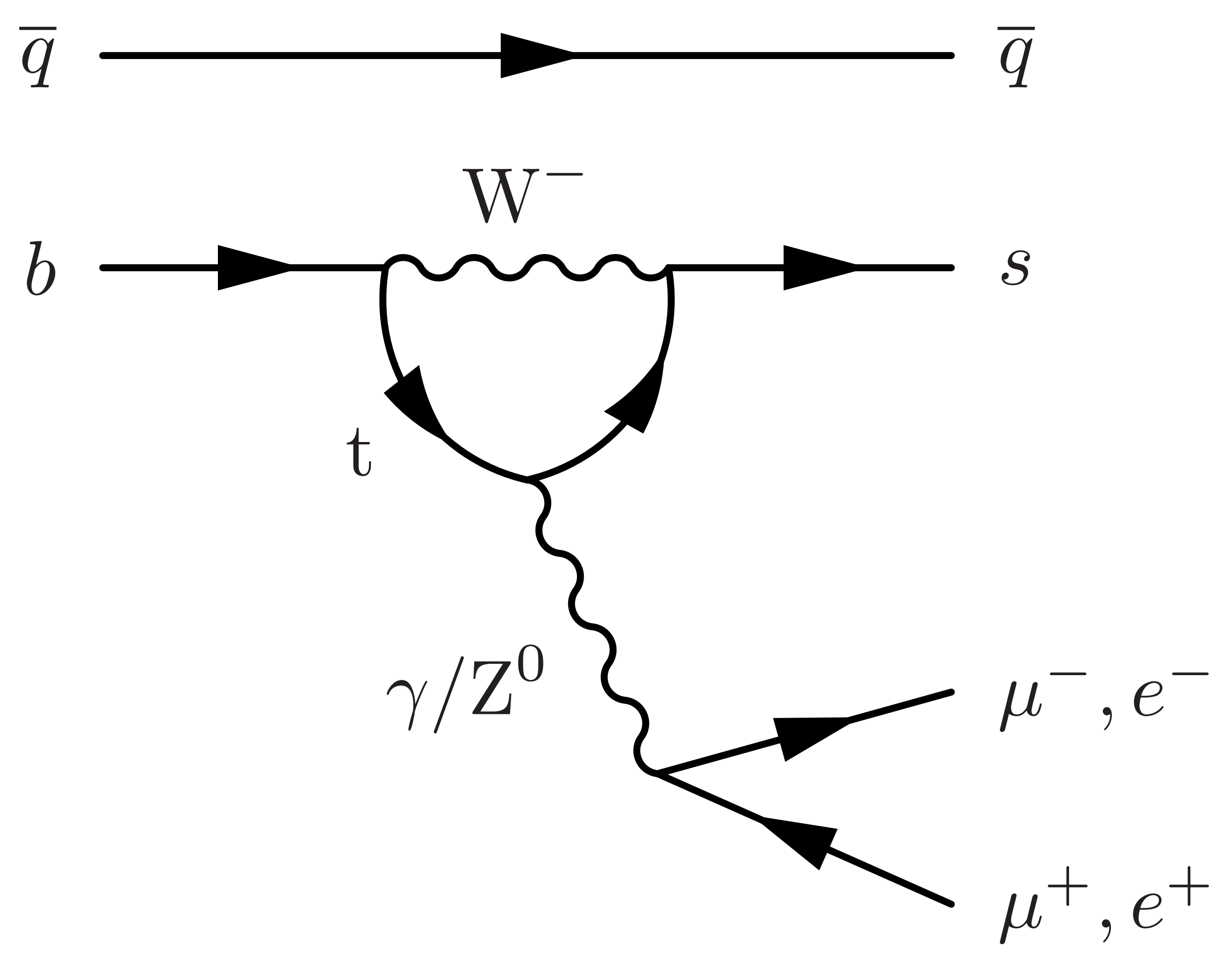
Si-strips

Additional tracking station

Lepton Flavour Universality tests

- $b \to s\ell\ell$ processes excellent probe to test for LUV effects
- $R_{K^{(*)}}$ is close to unity in SM, with very small uncertainties
- Extremely clean test:
  - cancellation of hadronic form-factors uncertainties in predictions
  - Possible deviation from QED corrections ~1% below $c\bar{c}$ resonance Bordone, Isidori, Pattori EPJC(2016)76:440
- Electrons are very challenging @LHCb!

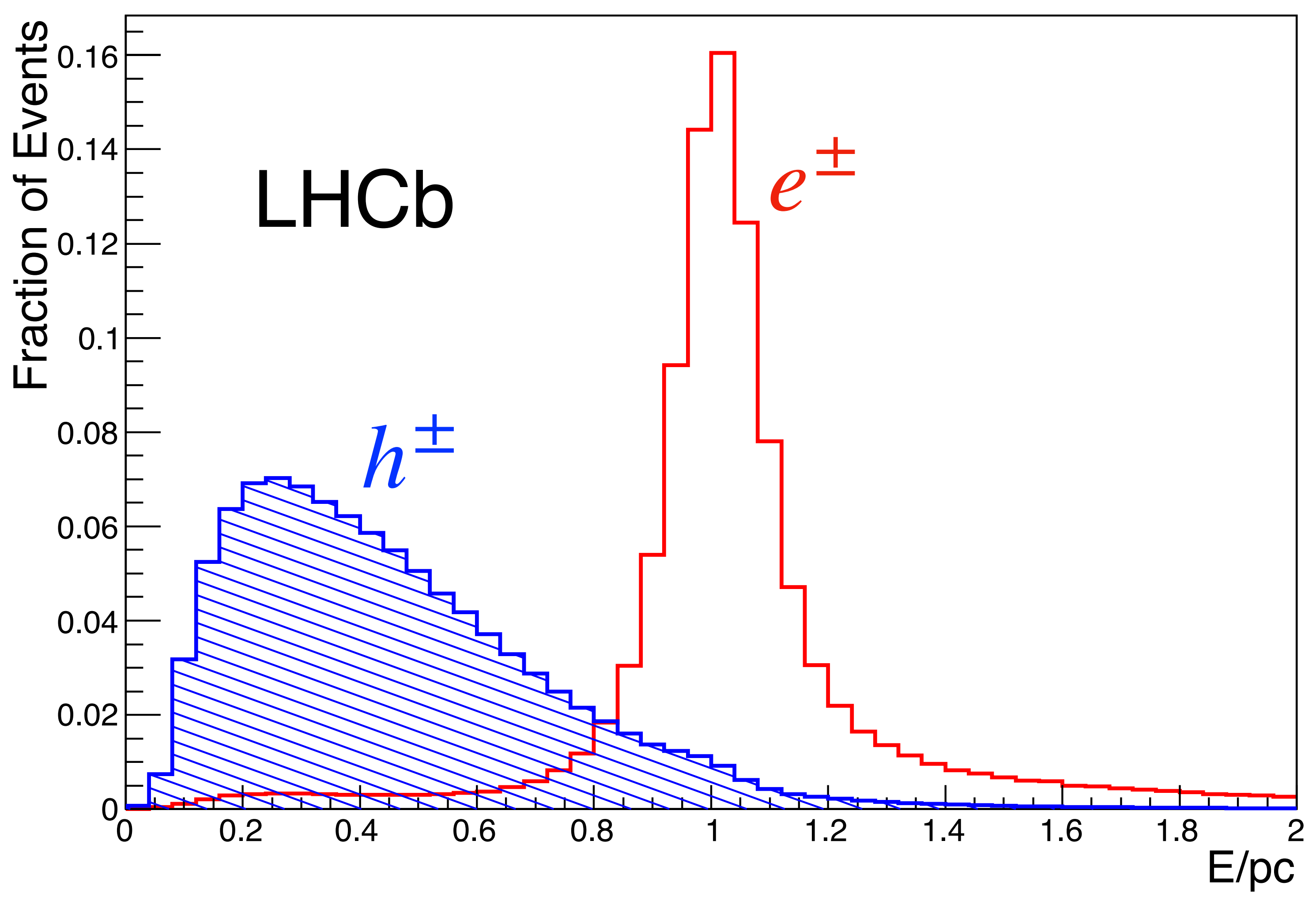
$$R_H = \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B \to H\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B \to He^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

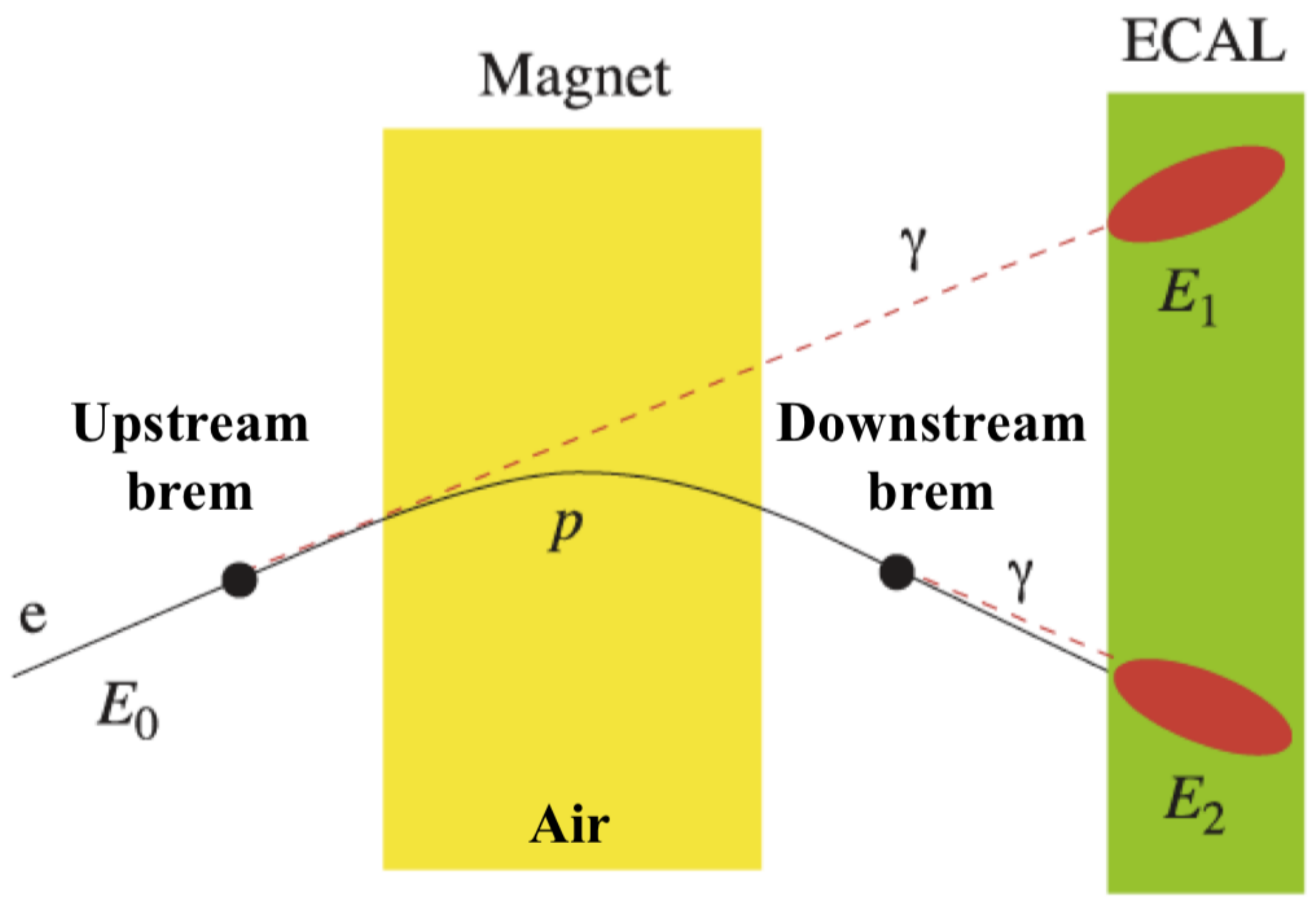


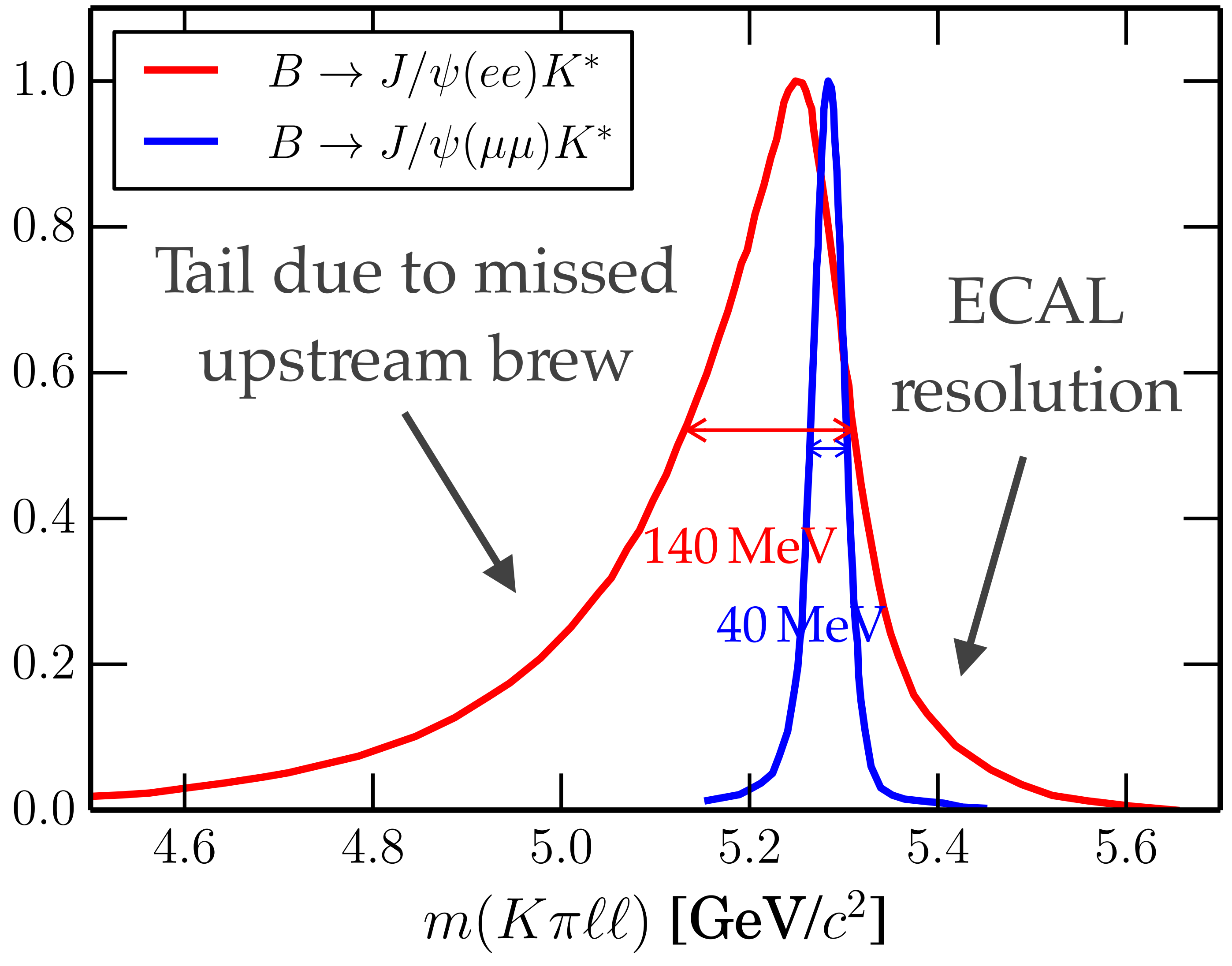
Electrons

Int.J.Mod.Phys. A 30, 1530022 (2015)

- Triggered on large energy deposit on calorimeter
- Electron ID based on calorimetric information
- Selection is a factor ~3 less efficient than muons
- Boosted *b*-hadrons from LHC collision: most electron emit hard bremsstrahlung photon
    - momentum resolution heavily affected.





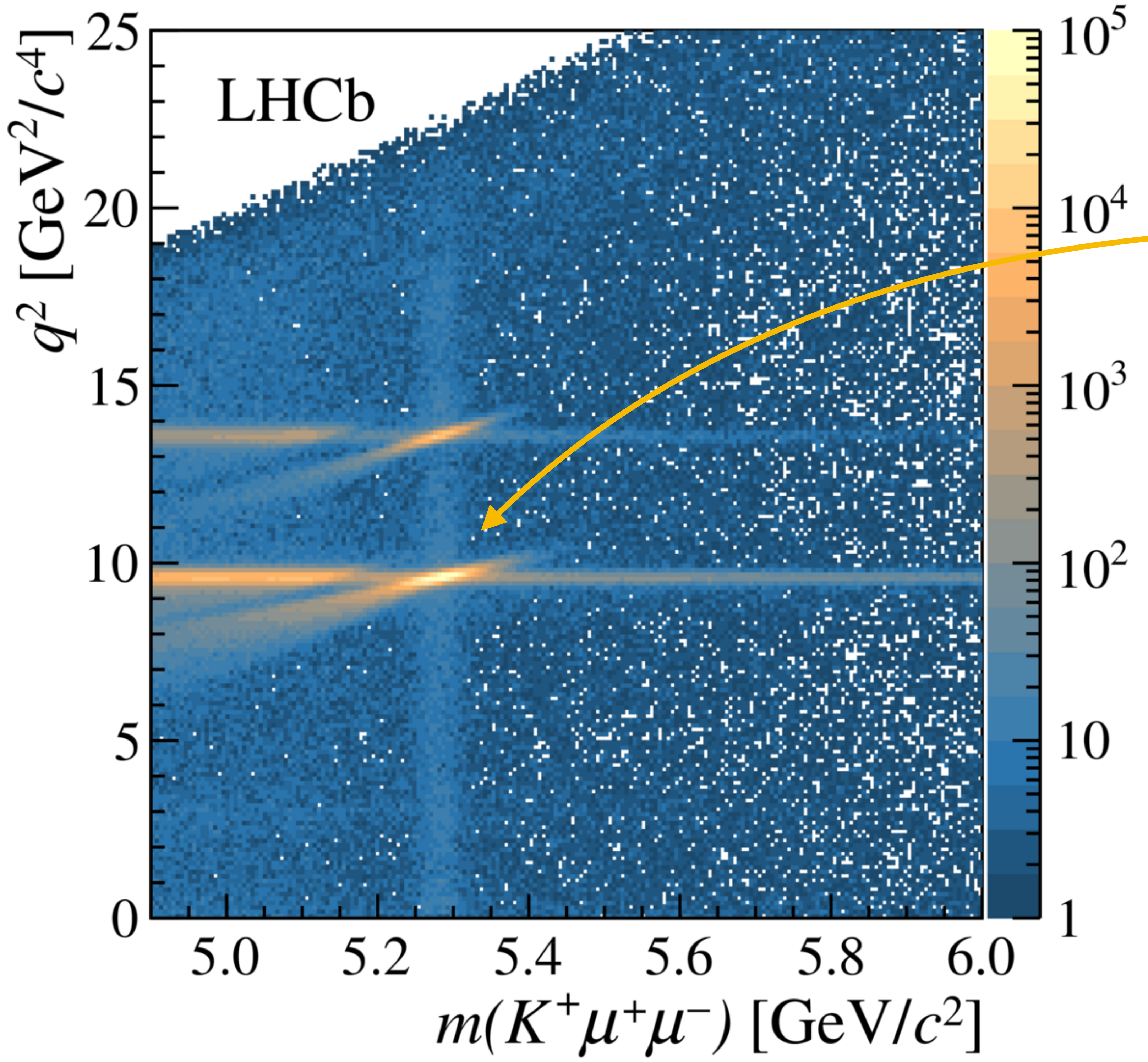


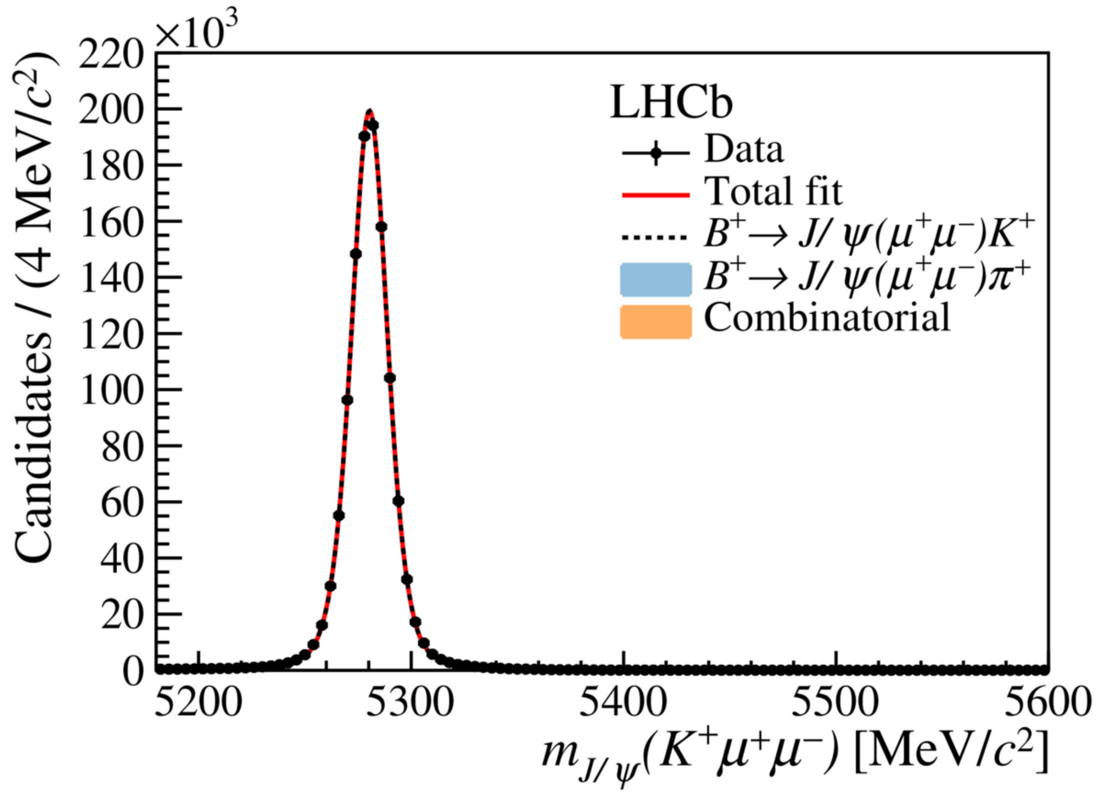
$B^+ \to K^+\ell^+\ell^-$ LFU tests

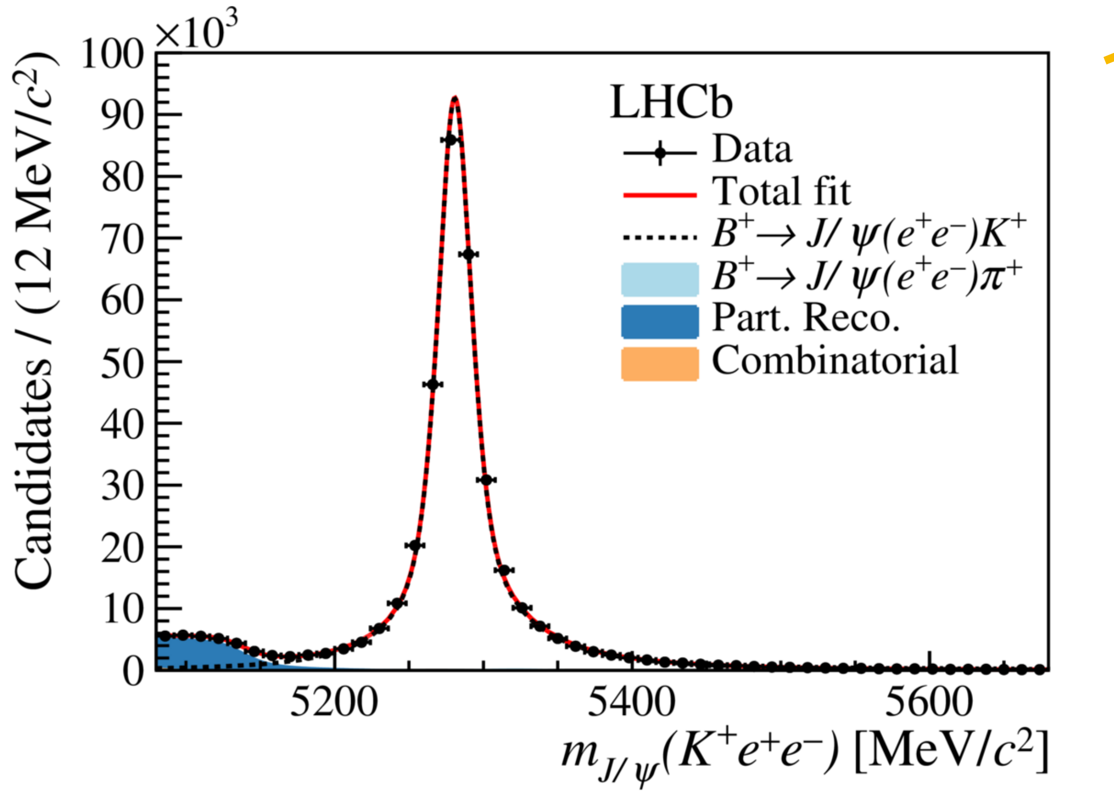
Phys. Rev. Lett. 122 (2019) 191801

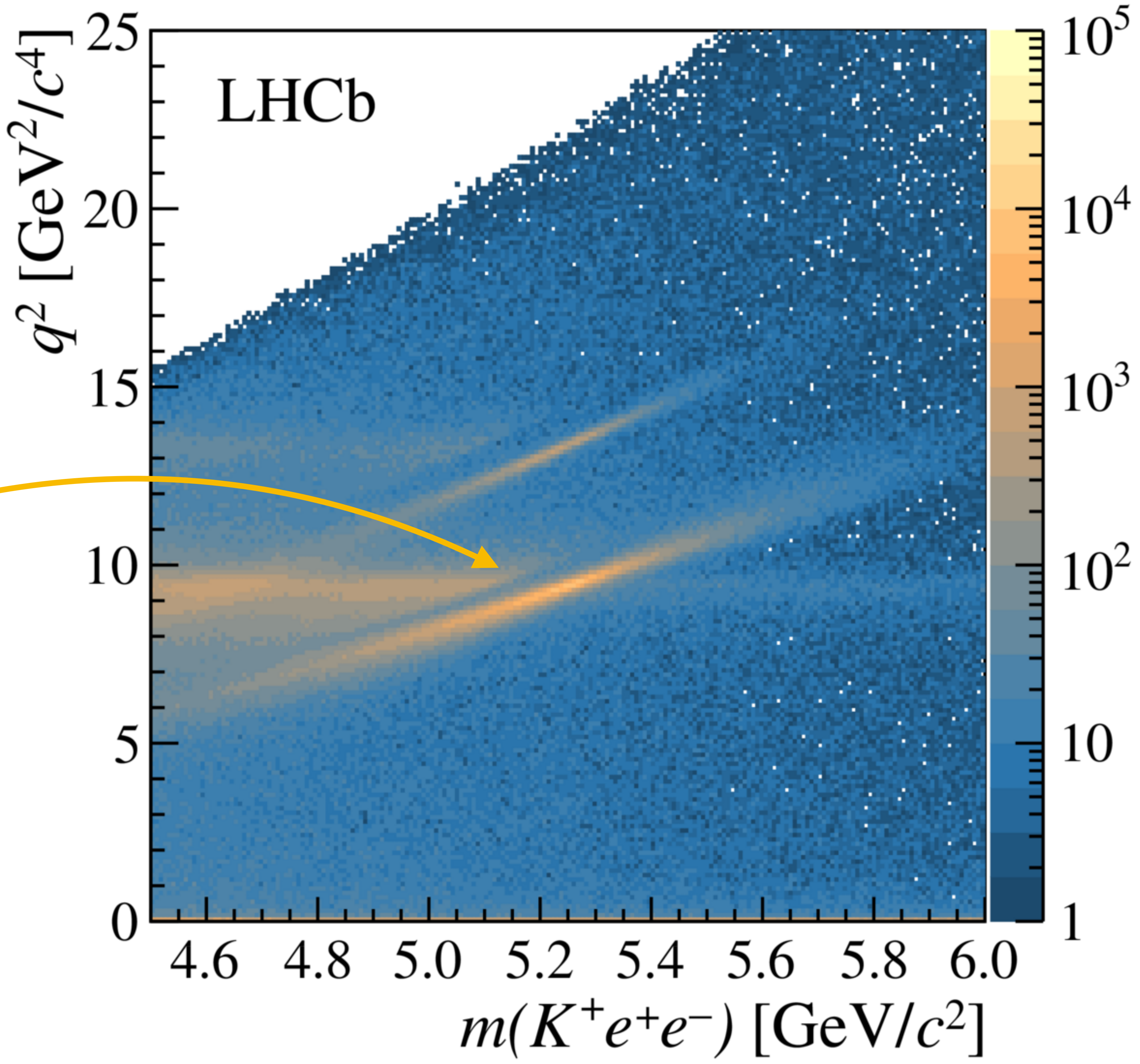
- Use of double ratio to further reduce systematics:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to e^+e^-)K^+)}$$







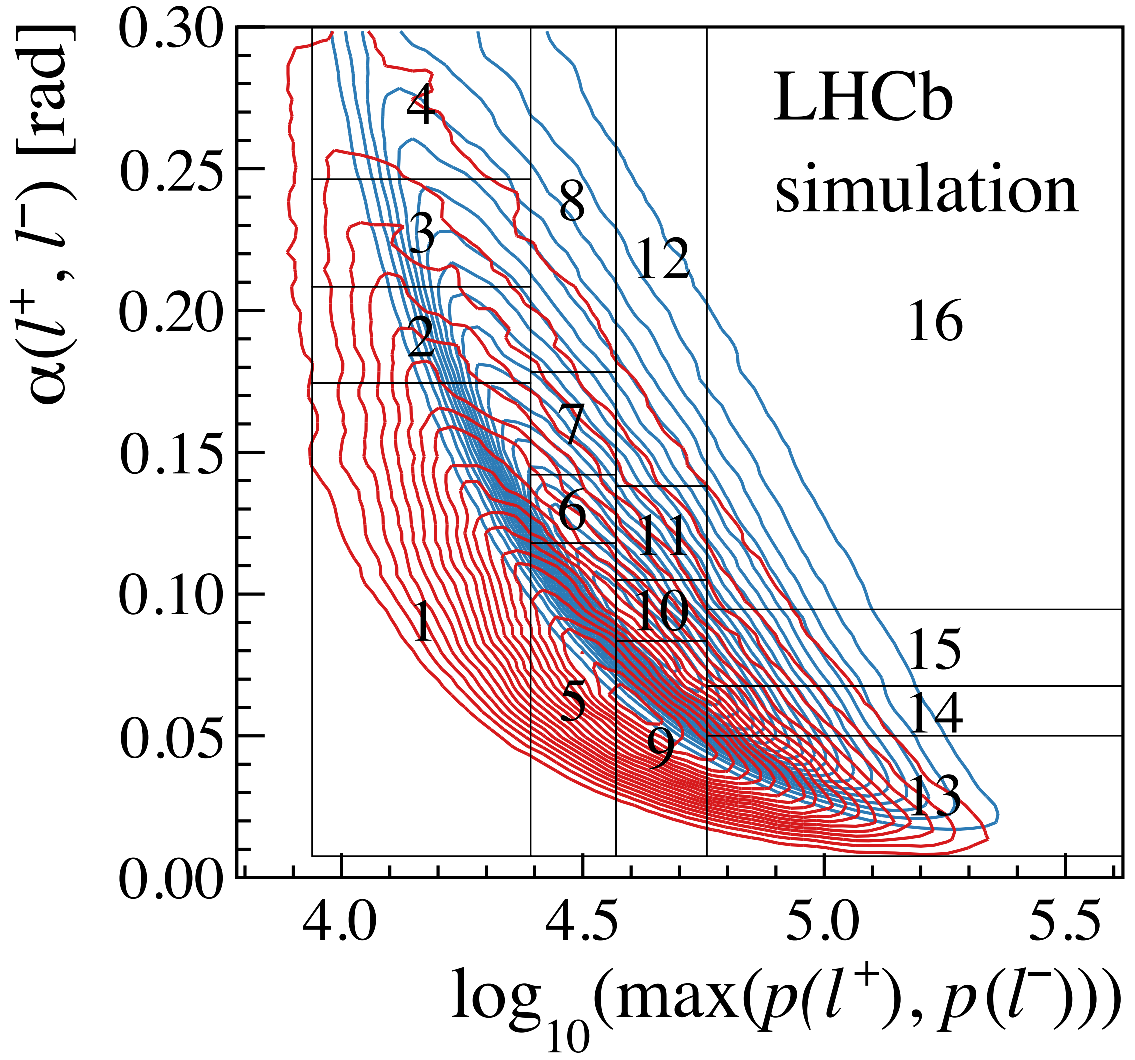


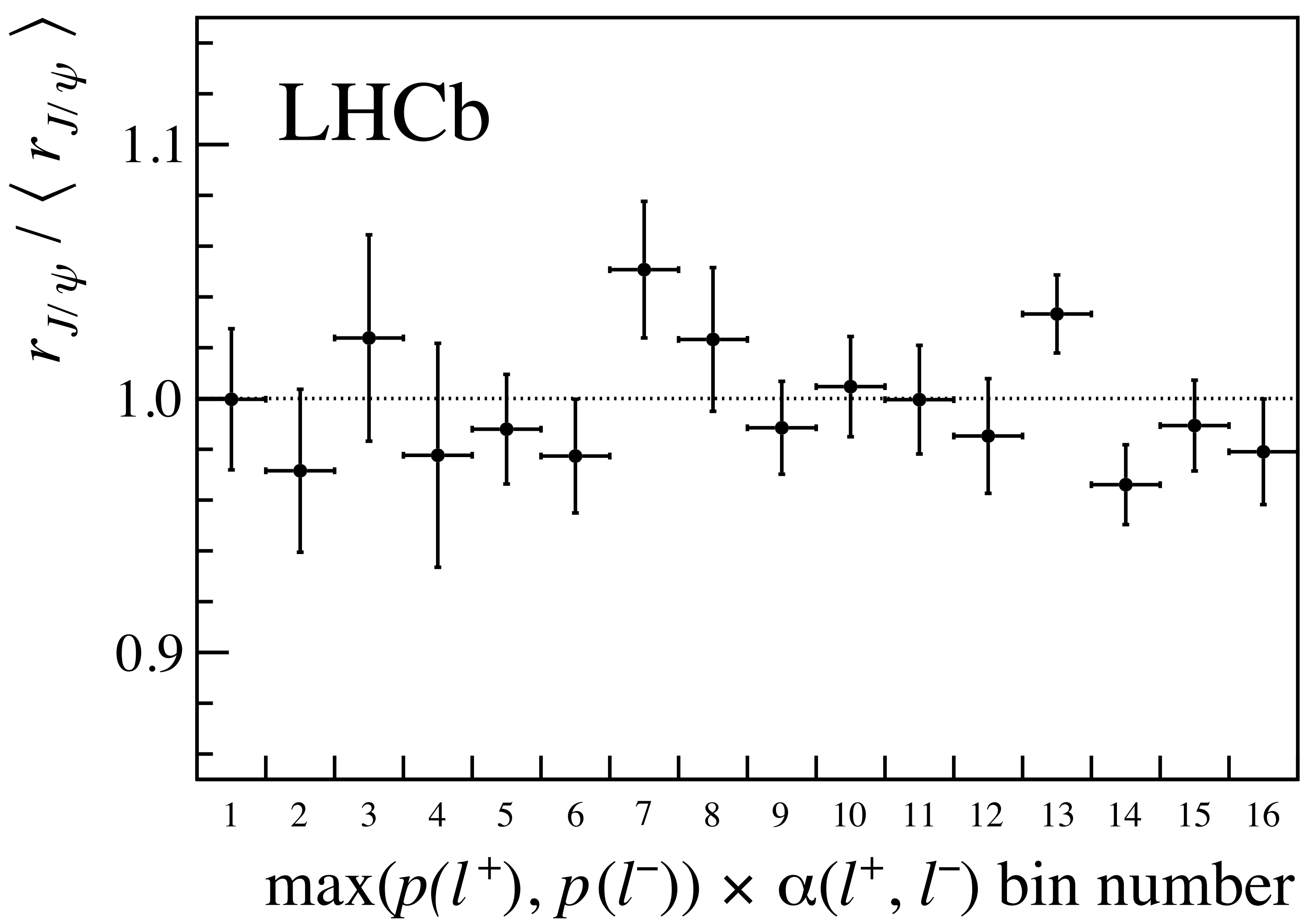
$B^+ \to K^+\ell^+\ell^-$ crosschecks

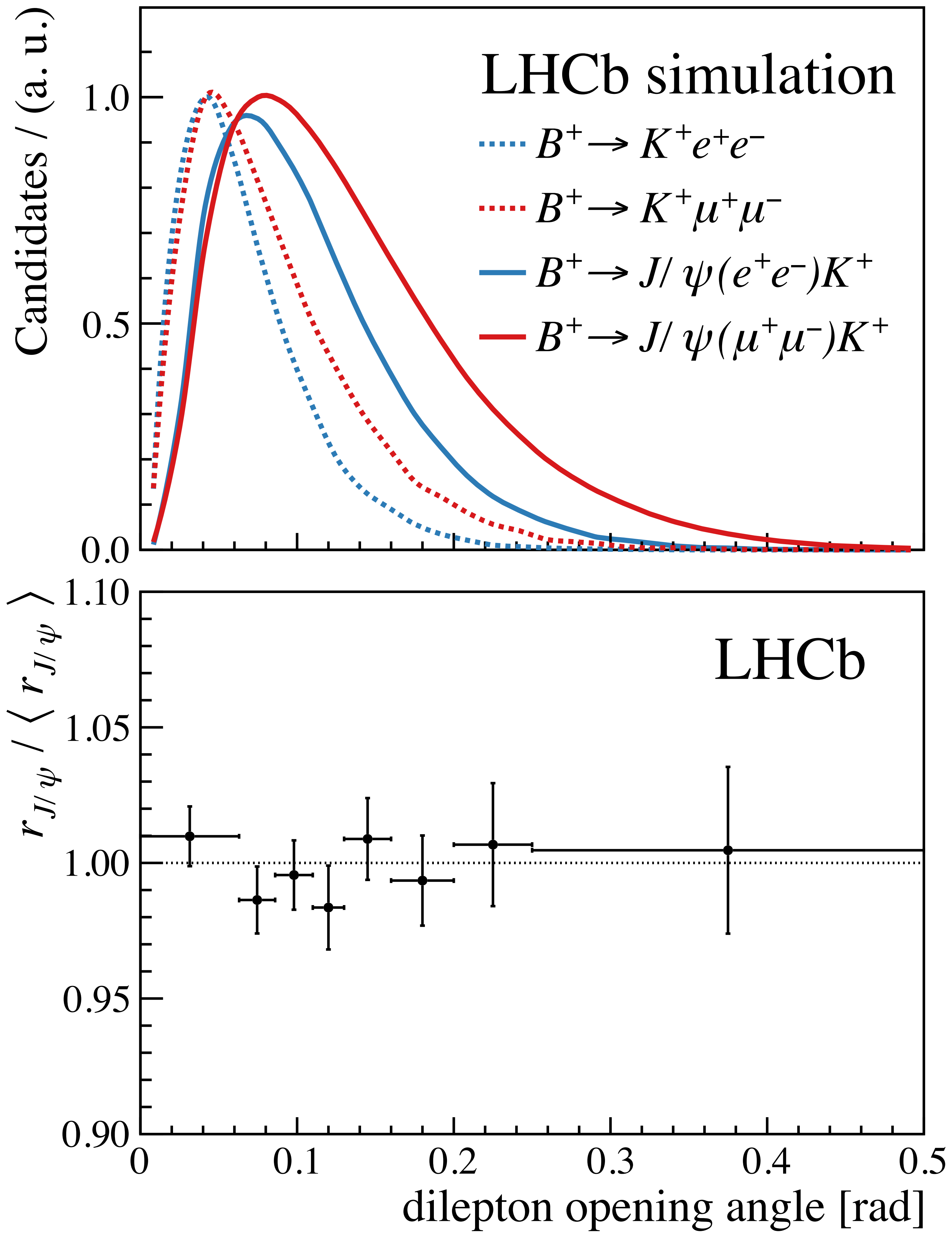
Phys. Rev. Lett. 122 (2019) 191801

- Crosschecks universality in $c\bar{c}$ resonances in all kinematic regions

$$r_{J/\psi} = \frac{\mathscr{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathscr{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 1$$







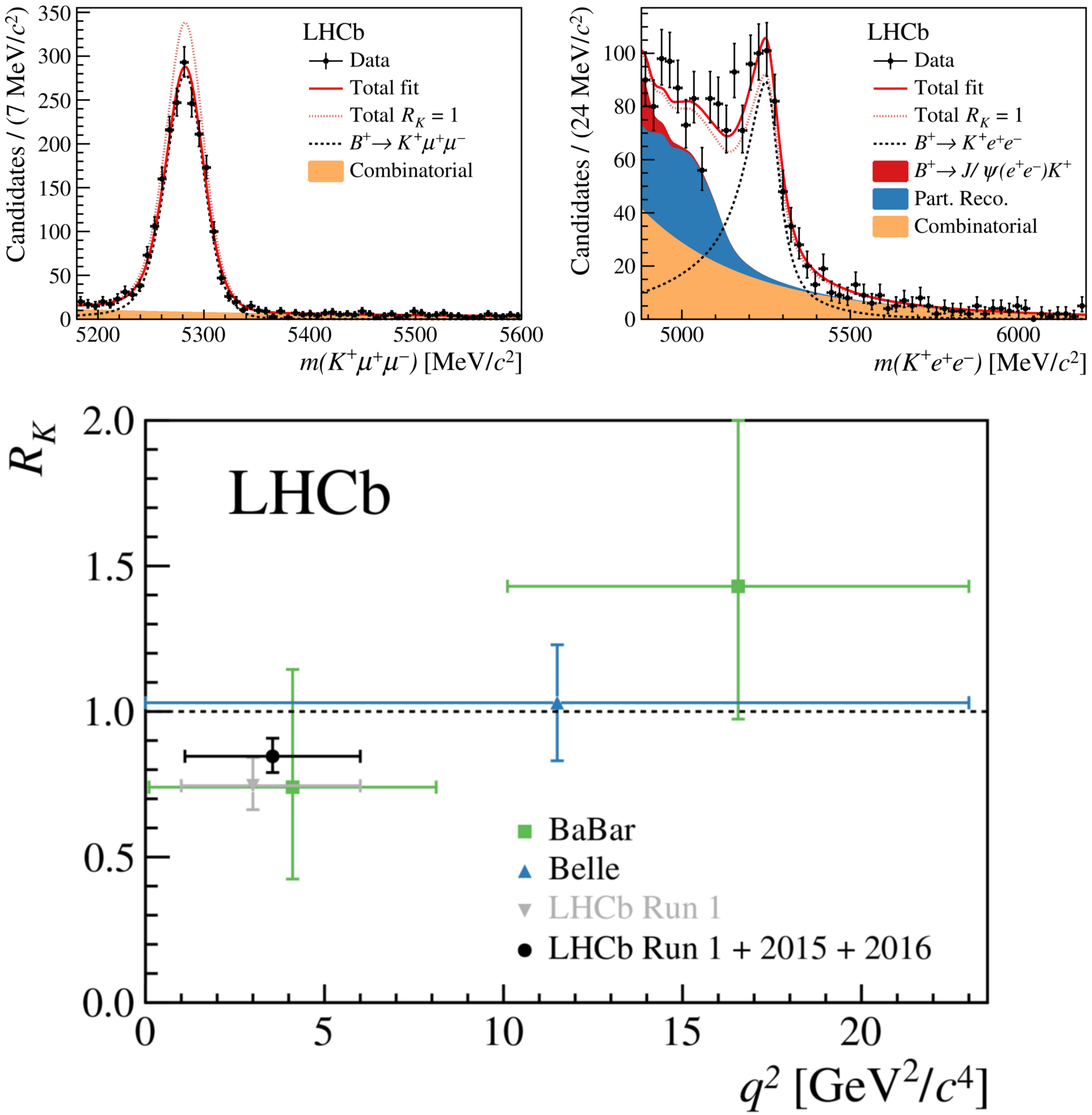
- Can also test that R_K measured at the $\psi(2S)$ is 1

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = 0.986 \pm 0.013\ (\mathrm{stat} + \mathrm{syst})$$

$B^+ \to K^+\ell^+\ell^-$ LFU tests

Phys. Rev. Lett. 122 (2019) 191801

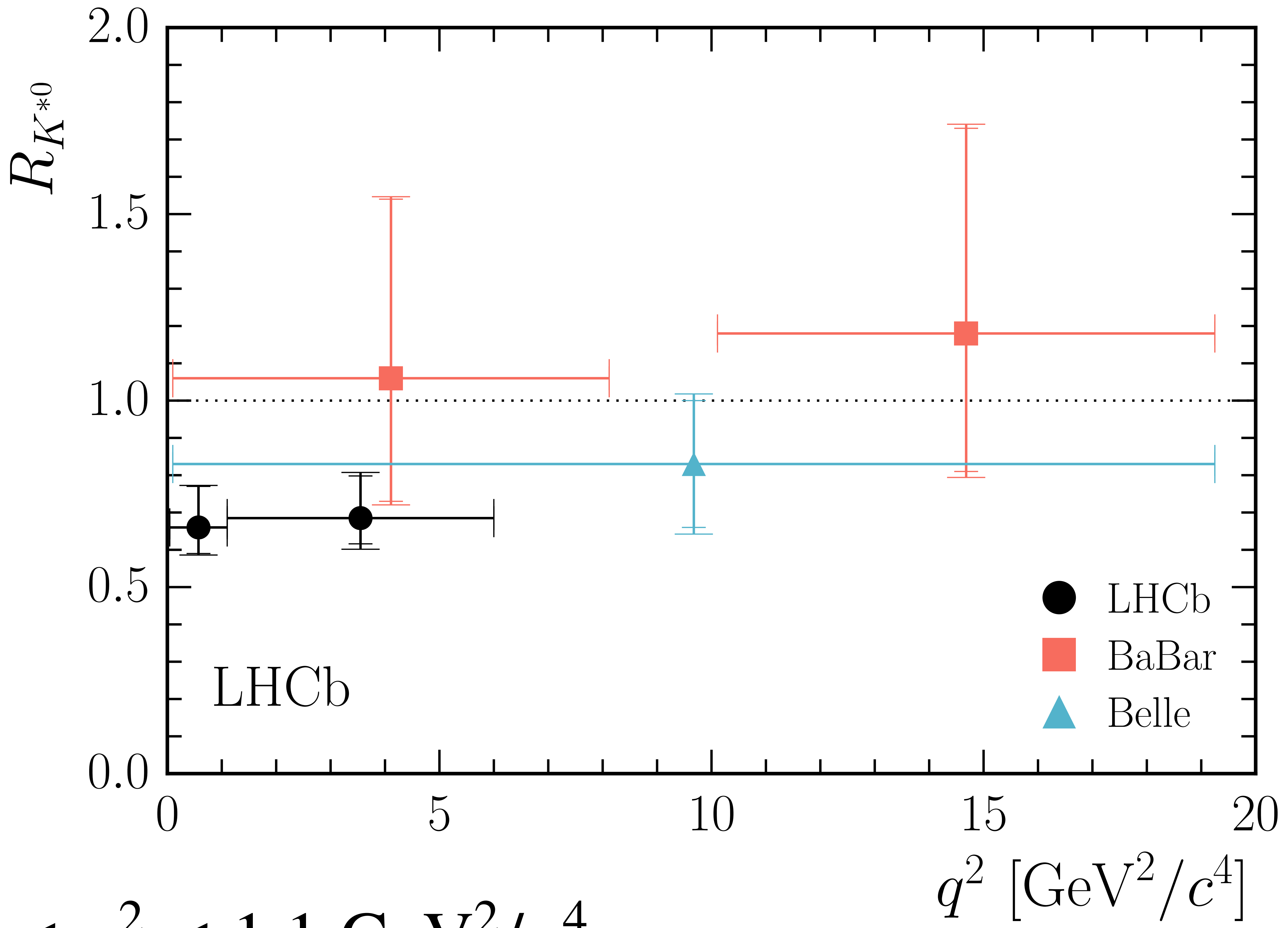
- Measurement with 2011-2016 (~5 fb^{-1} at $\sqrt{s}$ = 7,8 and 13 TeV) in central q^2 bin [1-6]GeV^2
  - $R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$
- Yield of ~766 $B^+ \to K^+e^+e^-$ events vs ~1943 $B^+ \to K^+\mu^+\mu^-$ driving the total uncertainty:
  - 7% statistical error vs 2% systematic
- R_K is found to be lower than 1 by ~15%
  - Still compatible with the SM at 2.5σ level!



$B^0 \to K^{*0}\ell^+\ell^-$ LFU tests

JHEP 08 (2017) 055

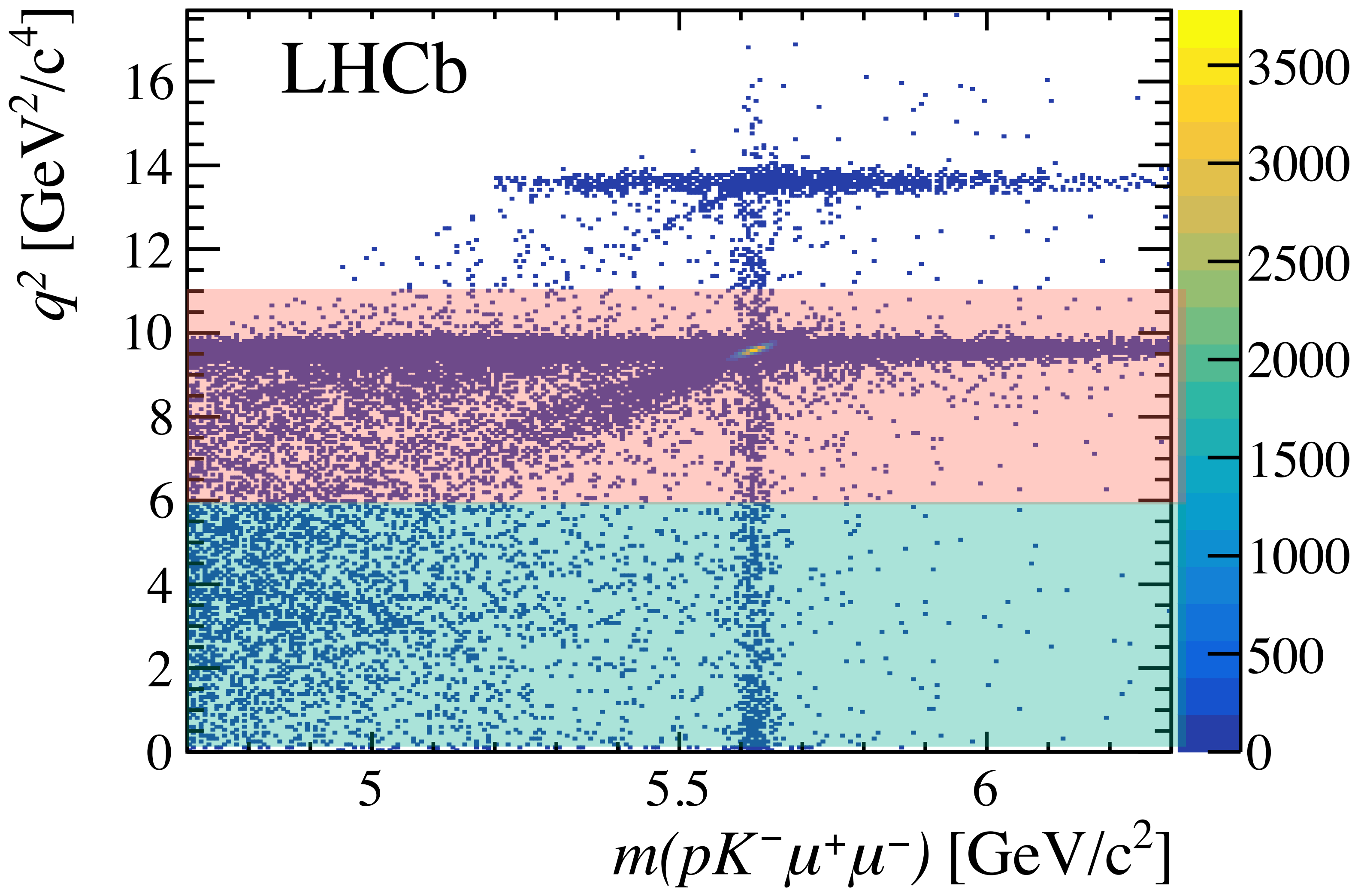
- Results use Run1 data ~3fb^{-1} of integrated luminosity
- Precision of ~17% in both bins, statistically dominated
- Upcoming Run1+Run2 analysis expected to reduce uncertainty by a factor ~2

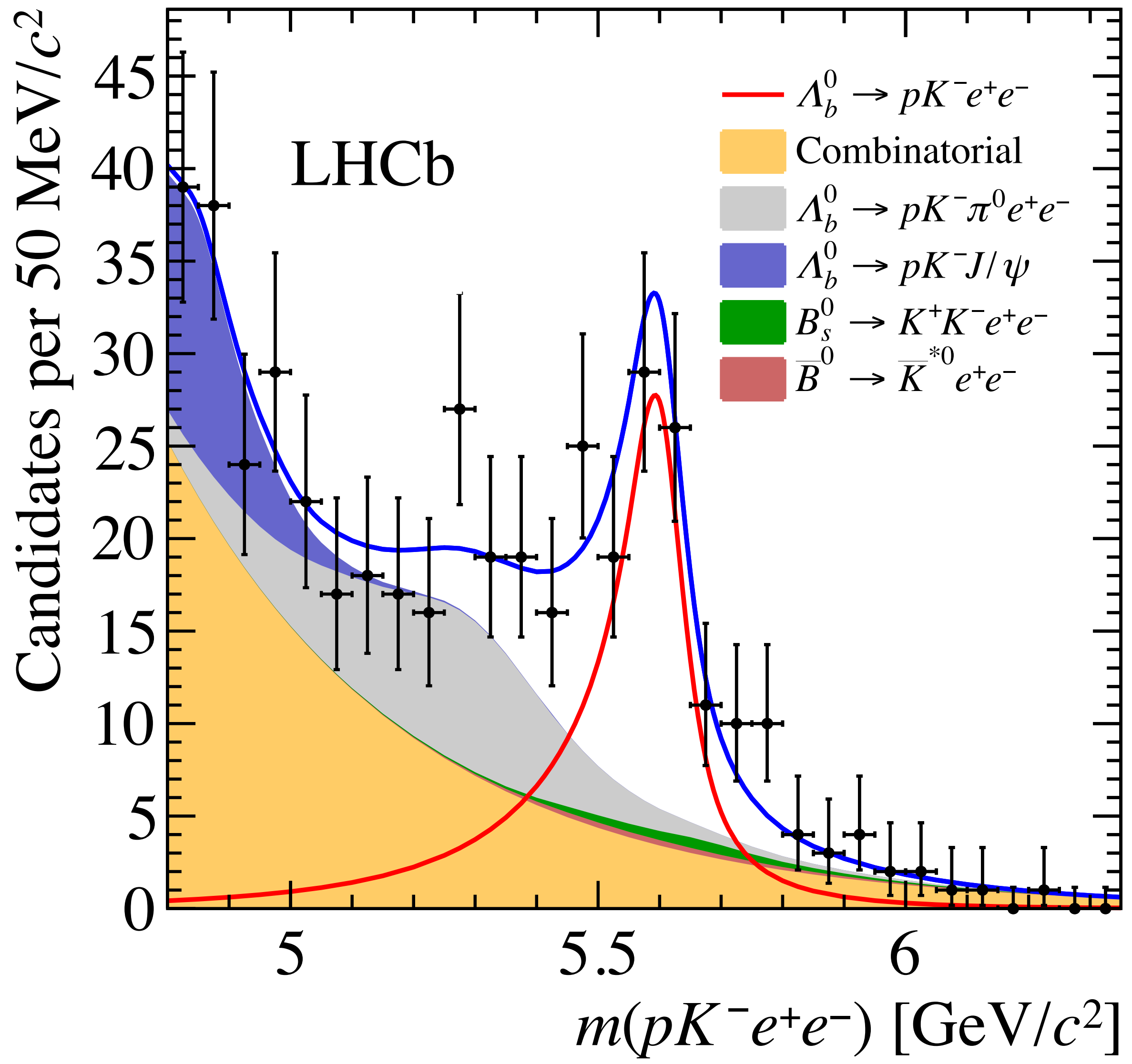


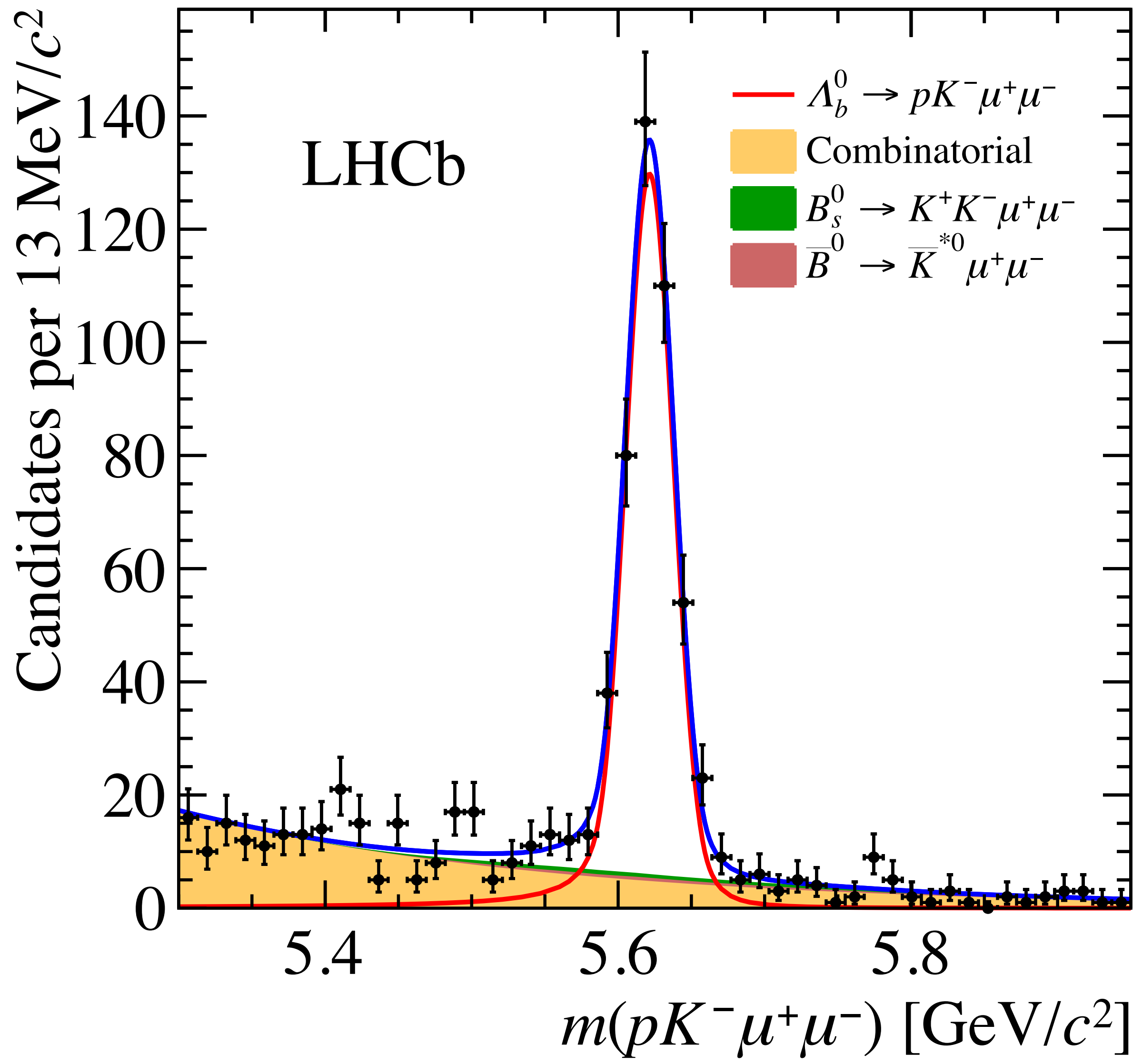
$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat})\,^{+0.03}_{-0.05}\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat})\,^{+0.05}_{-0.05}\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.1\ \text{GeV}^2/c^4 \end{cases}$$

LFU test with baryons

JHEP 05 (2020) 040







- First test of LU with b-baryons, using $\Lambda_b^0 \to pK\ell^+\ell^-$ decays, analogous to $R(K^{(*)})$, expected to be unity in the SM [Fuentes-Martin et al.]

- Analysis performed using Run1 + 2016 dataset

- Region considered for the measurement: $m(pK^-) < 2.6$ GeV$/c^2$ and $0.1 < q^2 < 6$ GeV$^2/c^4$

- Efficiency crosschecked with resonant J/ψ component in $6 < q^2 < 11$ GeV$^2/c^4$

LFU test with baryons

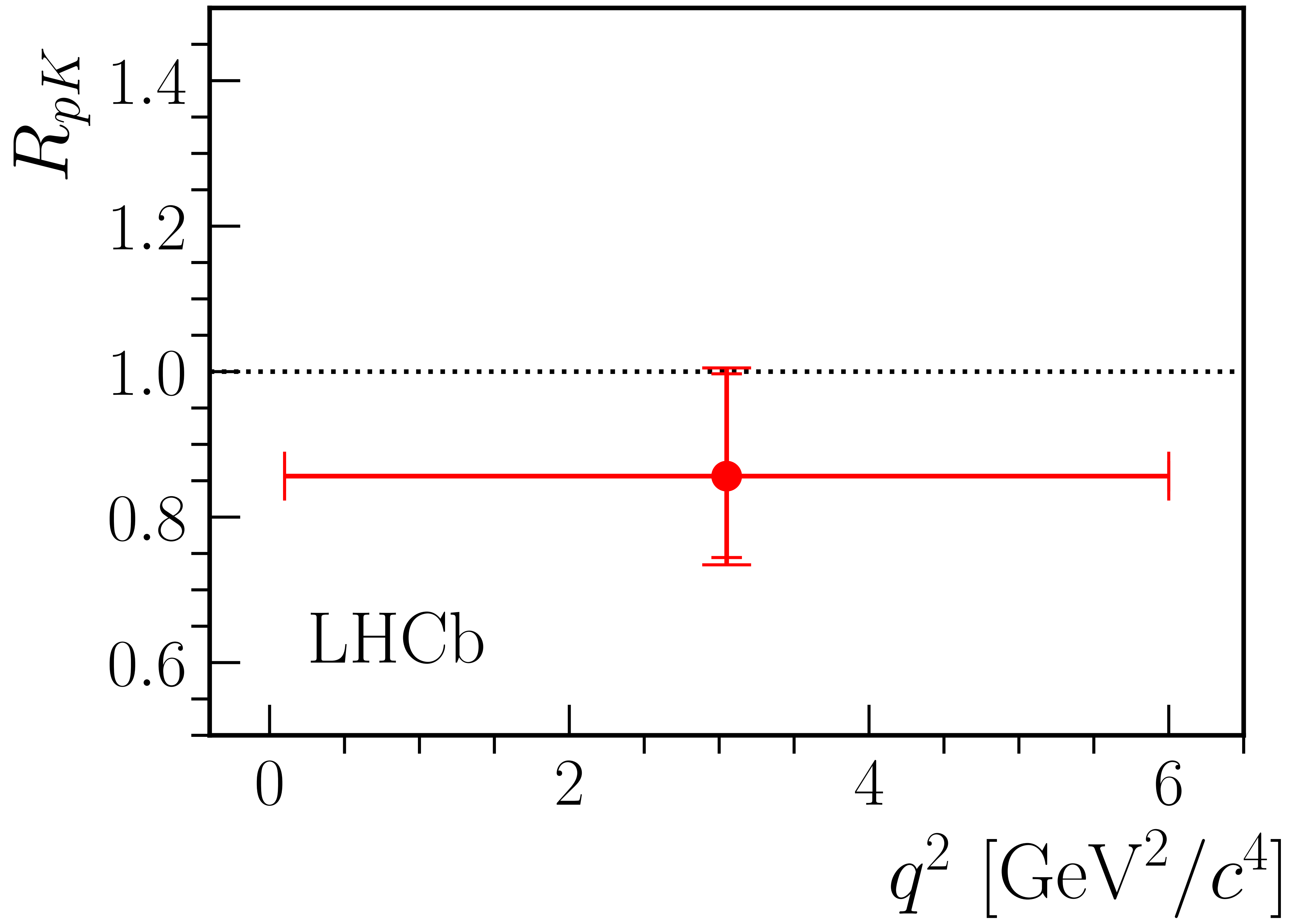
JHEP 05 (2020) 040

- First observation of $\Lambda_b^0 \to pKe^+e^-$ with more than 7σ

$$\mathscr{B}(\Lambda_b^0 \to pKe^+e^-)\Big|_{0.1<q^2<6\mathrm{GeV}^2/c^4} = (3.1 \pm 0.4 \pm 0.2 \pm 0.3 \pm^{0.4}_{0.3}) \times 10^{-7}$$

$$\mathscr{B}(\Lambda_b^0 \to pK\mu^+\mu^-)\Big|_{0.1<q^2<6\mathrm{GeV}^2/c^4} = (2.65 \pm 0.14 \pm 0.12 \pm 0.29 \pm^{0.38}_{0.23}) \times 10^{-7}$$

$$R_{pK}\Big|_{0.1<q^2<6\mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05$$



Prospects for R_X measurements in LHCb

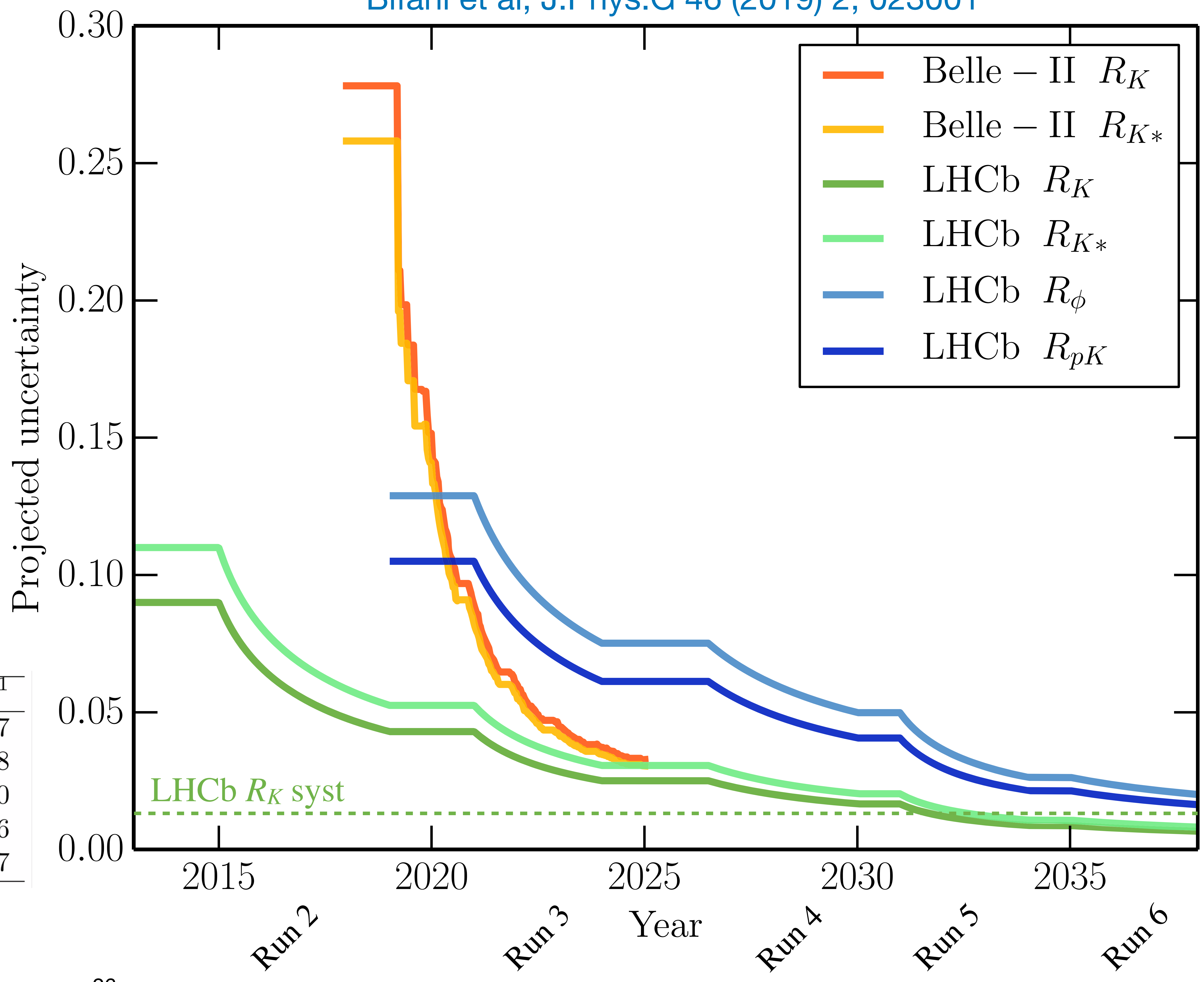
- Precision driven by the electron mode and projection based on the current performances

- R_K hitting QED uncertainty during Run 6

- **Higher statistics will give access to additional observables such as R_π**

R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

Bifani et al, J.Phys.G 46 (2019) 2, 023001



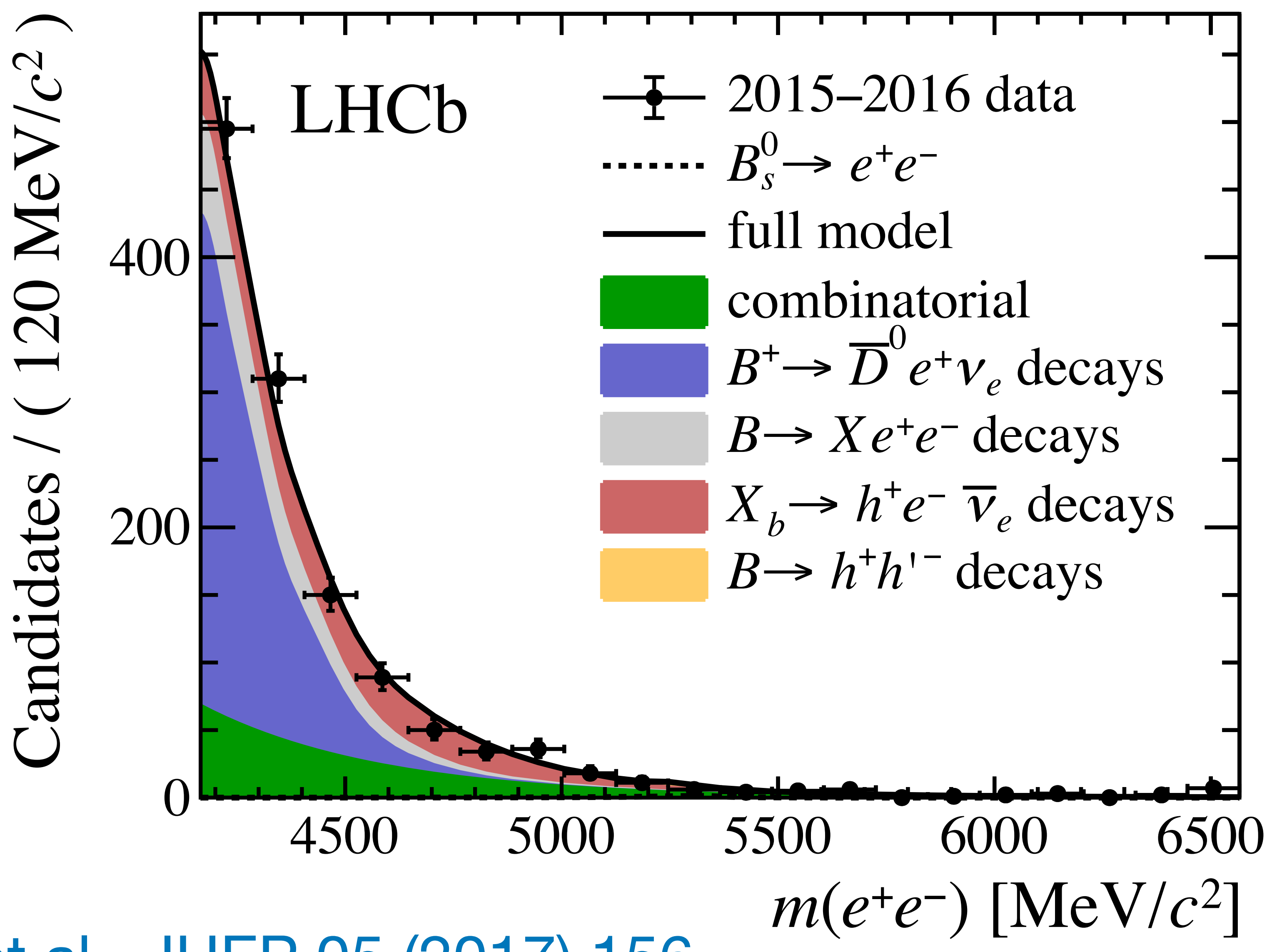
Test of LFU with $B^0_{(s)} \to e^+e^-$ decays

- Helicity suppressed by $\mathcal{O}(10^{-4})$ relative to $B^0_{(s)} \to \mu^+\mu^-$
- $\mathcal{B}(B^0_s \to e^+e^-) = (8.35 \pm 0.39) \times 10^{-14}$
- $\mathcal{B}(B^0 \to e^+e^-) = (2.39 \pm 0.14) \times 10^{-15}$

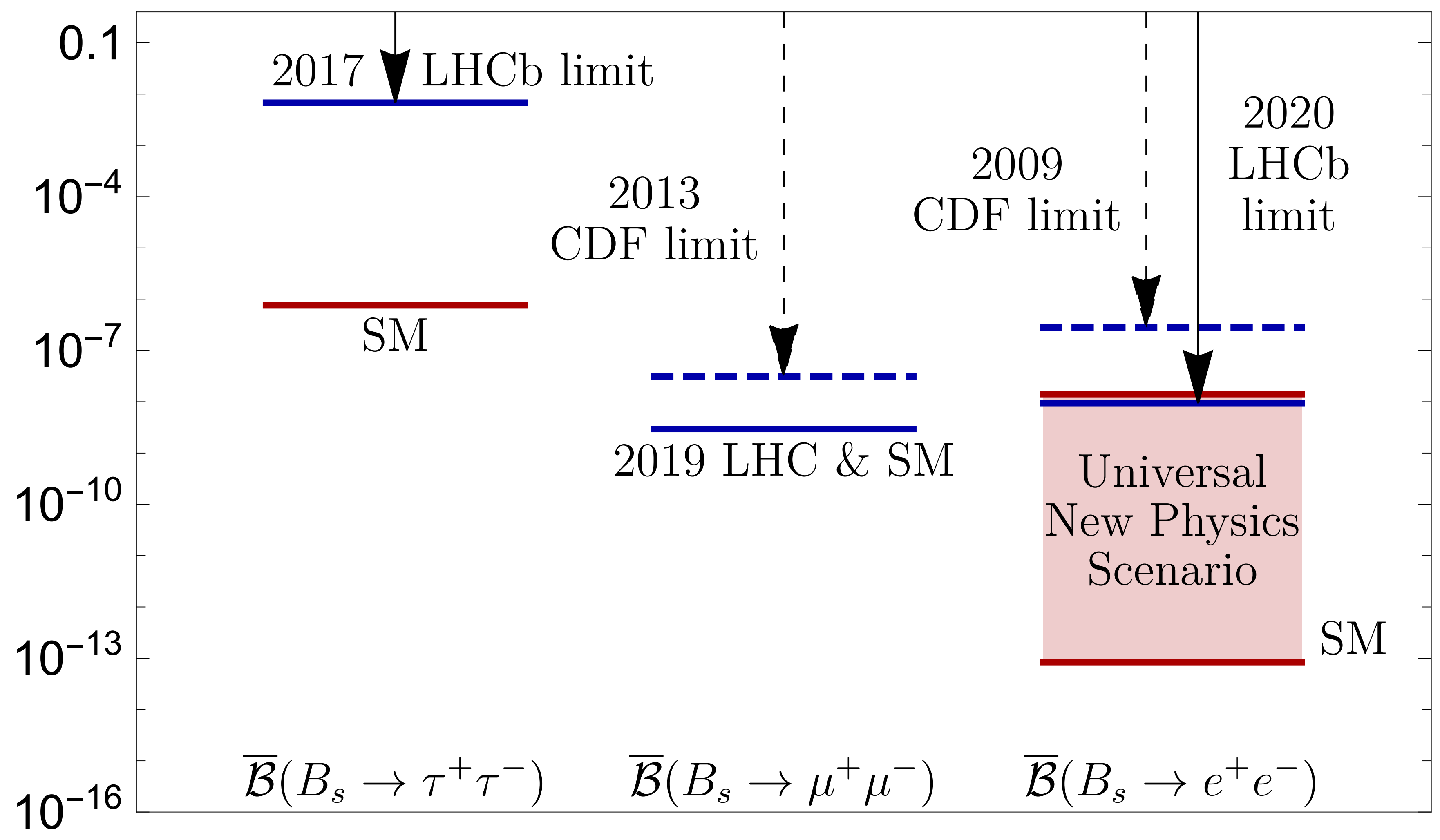
M. Beneke et al. JHEP 10 (2019) 232

- NP effects could increase BFs by $\mathcal{O}(10^6)$
- Current analysis performed on Run1+2015+2016 data
- Signal extracted from UML fit on $m_{e^+e^-}$
  - $\mathcal{B}(B^0_s \to e^+e^-) < 11.2 \times 10^{-9}$ at 95 % CL
  - $\mathcal{B}(B^0 \to e^+e^-) < 3.0 \times 10^{-9}$ at 95 % CL

Phys. Rev. Lett. 124 (2020) 211802



Fleischer et al., JHEP 05 (2017) 156



Prospects

- $B_s^0 \to e^+e^-$ already probing possible LUV scenarios
- Potential backgrounds like $B_s^0 \to e^+e^-\gamma$ might become relevant with larger statistics
- Electron reconstruction/PID unknown after UpgradeII
- Also $B_{(s)}^0 \to \tau^+\tau^-$ even if far from SM expectations still powerful tool to constraint NP Leptoquark models
  Phys. Rev. D 94, 115021 (2016)
- Run1: $\mathscr{B}(B_{(s)}^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ @ 95 % CL
- 300 fb–1: $\mathscr{B}(B_{(s)}^0 \to \tau^+\tau^-) < 2.6 - 5 \times 10^{-4}$ @ 95 % CL